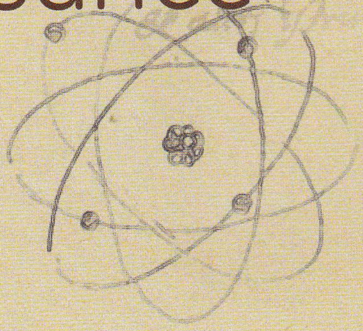
# Orbit

Volume 26 • Number 3 • 2006

## A Nuclear Renaissance

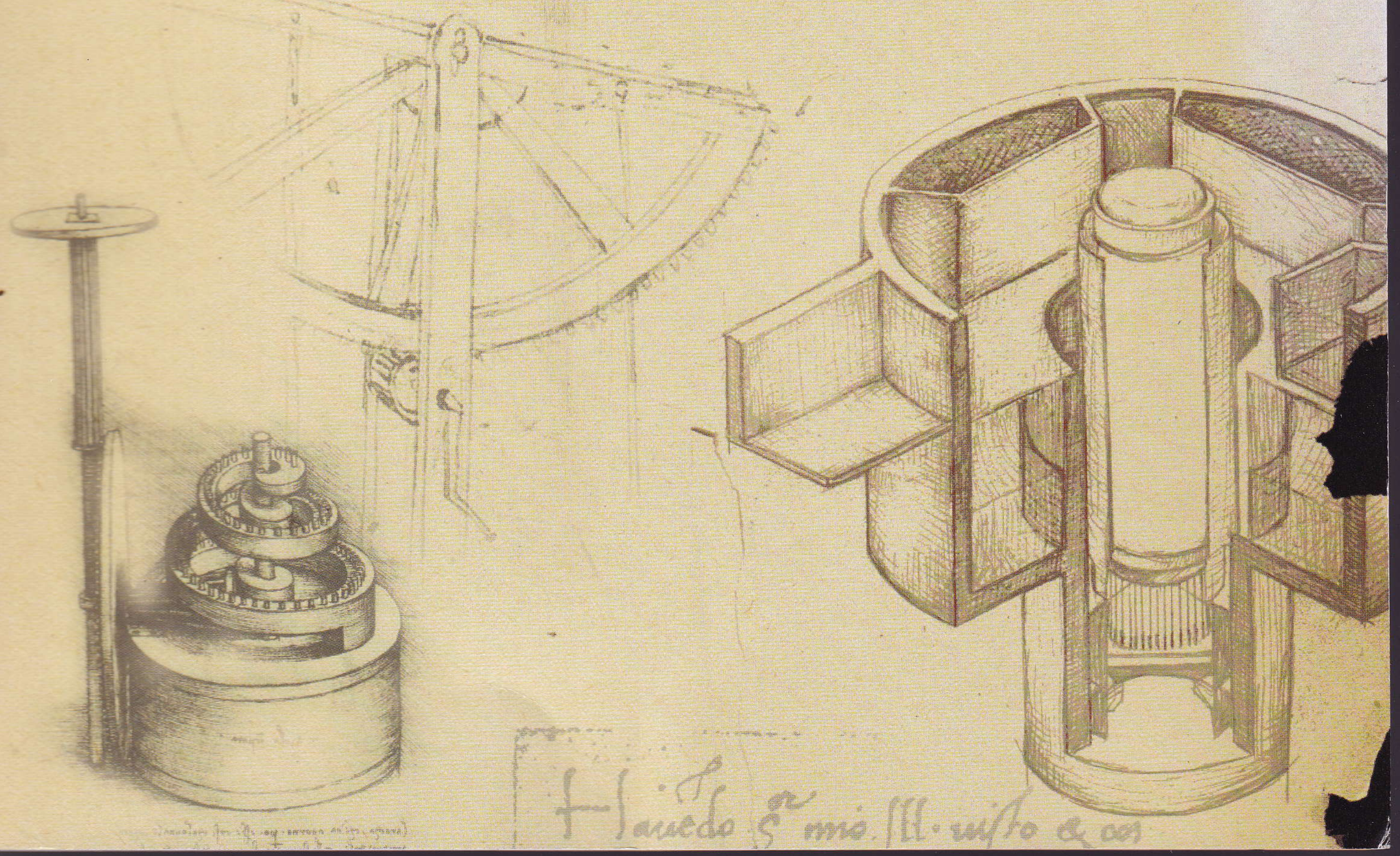


The New Era of Nuclear Power

Case History: Integrated Performance and Condition Monitoring at DuPont

Case History: Shaft Crack Detection Methodology for Reactor Coolant & Recirculation Pumps

New ADRE® Replay Card and Nuclear Sensors



# Orbit

A Technical Publication for Advancing
the Practice of Operating Asset Condition
Monitoring, Diagnostics, and
Performance Optimization

**Vol.26 No.3 2006**

Publisher
**GE Energy**

Editor
**Steve Sabin**

Design & Production Coordination
**Earl Stewart**

Design
**Gina Alteri**

Circulation
**Karen Schanhals**

Printer
**RR Donnelley**

ORBIT is published three times per year
by GE Energy and is available online at
www.ge-energy.com/orbit

Questions, suggestions, and letters to
the editor may be addressed to:
ORBIT Magazine
1631 Bently Parkway South
Minden, Nevada USA 89423
Phone: 775.782.3611
Fax: 775.215.2864
e-mail: orbit@ge.com

Printed in the USA
Over 40,000 copies
distributed worldwide

Copyright © 2006 General Electric Company
All rights reserved.

GEA-14393

## A Nuclear Renaissance

My earliest recollection of nuclear power was as a middle school student on a field trip to the Trojan Nuclear Plant. I remember very little about the trip other than the vague sense that splitting atoms to generate heat was "high tech" compared to the logs that fueled the quaint wood-burning stove we used to heat our home. On second thought, I remember one other thing—ardently wishing for a way to safely harness that technology on a residential basis because it would mean I no longer had to split and stack wood, my most dreaded of all chores.

I hadn't really thought much about the plant until this summer, nearly 30 years later, as I headed north on the first leg of a vacation road trip. It made me feel, well, old, to see that the plant had been completely de-commissioned with even the familiar-shaped cooling tower no longer a part of the landscape visible from the freeway. There's nothing left anymore, unless you count the very cool video of the tower being dismantled floating around on the internet at places like www.youtube.com.

For the last several decades, many of us have assumed that nuclear power was a dying breed, as extinct as the dinosaurs whose remains we now burn in our fossil-fueled plants. But with new concerns over the effect those same fossil fuels may be having on the global environment, nuclear is no longer the bad word it was even 10 years ago, leading to a resurgence in interest. In this issue of ORBIT, GE's Brian Jordan takes an in-depth look at the nuclear power generation industry—where it's been, where it's going, what's driving it—and concludes with a conversation with Andy White, President and CEO of GE Energy's nuclear business. We introduce you to some new products, including vibration transducers specifically designed for nuclear environments, and we provide our usual assortment of applications articles and case histories, including one that examines the shaft crack problems that can plague the coolant and recirculation pumps common in many nuclear plants.

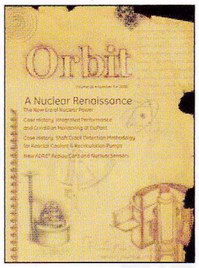
Even if you aren't directly involved in the nuclear power industry, I'm confident you'll find something of interest in this issue. With each publication of ORBIT, our mission is to provide useful technical information on monitoring and optimizing your plant's assets, applicable to just about any industry where machinery is used. As we finish our 26th year of bringing this magazine to you, it's good to know we're succeeding in that mission.

**Steve Sabin**
Editor

# Orbit

**A Technical Publication for Advancing the Practice of Operating Asset Condition Monitoring, Diagnostics, and Performance Optimization**

Vol.26 No.3 2006



## Cover Story

24 The New Era of Nuclear Power

## Case Histories

4 Integrated Performance and Condition Monitoring at DuPont

38 Shaft Crack Detection Methodology for Reactor Coolant & Recirculation Pumps

## New Product Showcase

20 ADRE® Digital Replay Card

21 Radiation Resistant 3300 XL Proximitor® and 330530 Velomitor® Sensor

22 3300 XL Underwater Probes

## Recip Tips

22 When is Rod Drop the Right Measurement for Reciprocating Compressors?

## Announcements

23 Unlocking the Potential: 2007 Optimization and Control Users' Conferences

31 Advancing the Nuclear Renaissance: 2007 Nuclear Instrumentation and Control Users' Conferences

61 REGCO of Thailand Recognized for Excellence in Technology Optimization

61 2007 Training

## From the Desk Of

36 More Technology...Closer to Our Customers

48 Synopsis of Savings

## Applications

50 Pipe Strain

CONTRIBUTORS

**GE Energy**

Ronald Bosmans, John Cataldo, Dave Fahy, Brian Jordan, Stephen Plaisance, Fritz Schweigert, Lane Swensen

CREDITS

eBay is a registered trademark of eBay, Inc. in the United States and other countries.

Six Sigma is a registered trademark of Motorola, Inc. in the United States and other countries.

All other registered (denoted by ®) or unregistered (denoted by ™ or ℠) marks used herein are the property of General Electric Company in the United States and other countries.

The Montreal Museum of Fine Arts for the following images:

- Codex Atlanticus, f. 26r/7r-a. Devices for a diver and for walking on water; water lifting devices (c. 1480-2).
- Manuscript of Madrid I, f. 45c. System for equalizing the release of a spring.
- Manuscript of Madrid I, f. 20v (detail). Ball-bearing.
- Codex Atlanticus, f. 138r/49v-a. Carriage-mounted crane.
- Codex Atlanticus, f. 1028r/391 r-a.

Provenance:

Codex Atlanticus, *Il Codice Atlantico di Leonardo da Vinci. Trascrizione diplomatica e critica di A. Marinoni* (new edition after restoration), Florence and New York, 1974-5; Florence 1975-80. First published by G. Piumati, 35 portfolios. Milan, 1894-1904.

Manuscript of Madrid I-II, Leonardo da Vinci, *The Madrid Codices*, ed. Ladislao Reti, 5 vols. New York, 1974.

# Integrated Performance and Condition Monitoring at DuPont

Monitoring systems have evolved from standing a nickel on its edge on top of the machine bearing cover or holding a screwdriver to one's temple, to high-speed simultaneous multi-channel data collection from permanently installed reliable vibration transducers and collaboration with process data from a myriad of sensors. Data from a host of platforms through numerous transmission protocols are displayed real time on CRT displays, LCD displays, or even high-definition plasma display screens and deposited into ever-increasing gigabytes of digital storage. Data processing overload by an ever-decreasing number of plant engineers is being addressed by an increasing number of willing vendors and contractors, all with the conceptual idea to relieve the overloaded remaining end-users. Today, plant personnel need a strategy to assimilate the data into useful information. At the heart of any effective asset management strategy—often a combination of condition-based, interval-based, and other approaches particular to the needs and economics of each asset—is a common thread: Information. Managing assets requires not just data, but information.

Stephen E. Plaisance
Technical Leader
Optimization and Control Services
GE Energy
steve.plaisance@ge.com

The Dupont Sabine River Works (SRW) plant in Orange, Texas, was DuPont's first operating ethylene plant when it opened in 1948. A new ethylene plant was placed in operation in May 1967 and continues to supply ethylene for use in the manufacture of ethylene copolymers at both the SRW and DuPont's Victoria, Texas, plant sites, and for export to other users in the United States' Gulf Coast region. The Ethylene unit consists of six major compressor trains: the Charge Gas Booster Compressor; the Charge Gas Compressor; the Methane Compressor; the Propylene Compressor (containing three stages); the Propylene Compressor with one side load and one extraction stage; and the Ethylene Refrigeration Compressor.

In 1995, the plant invested in coatings for its compressor rotors to combat the fouling that would periodically reduce flow rates and result not only in reduced production, but also in costly wash cycles and short-term turnarounds for more intensive cleanings. In 1997, the plant invested in Bently Nevada Performance Manager™ 2000 performance monitoring software to complement the existing Bently Nevada vibration monitoring platform, Data Manager® 2000. More recently, DuPont upgraded these systems to GE's System 1® software and Bently PERFORMANCE™ software respectively. This case history shows how the plant, in managing their operational risks, has utilized performance monitoring and vibration monitoring software.

System 1 optimization and diagnostic software is specifically designed to collect and manage asset-related data and convert that data to information using powerful embedded and fully customizable Decision Support℠ capabilities. Bently PERFORMANCE software extends the functionality of System 1 to include online thermodynamic performance monitoring of machinery.

## Steam Turbine Fouling – Performance Monitoring

The first performance part of this article deals with a steam turbine fouling issue that used performance data from the plant's Performance Manager™ 2000 software to assist in recovering production throughput. In 1999, the plant went into a turnaround to apply coatings to the steam turbines and verified that the compressor rotor coatings had the intended effect of reducing the typical fouling. A few months after returning to service, the Charge Gas Compressor steam turbine started to exhibit signs of fouling that was being seen in increased steam rates, lower efficiency, and reduced ethylene production. The root cause analysis led to the manual control of adding the chemicals for controlling boiler water chemistry, and steam quality problems arose with carryover that led to the fouling issue with the steam turbine[1]. An online water wash was conducted in January 2000. The red ovals in Figures 1-7 highlight the effects of the first online water wash that was conducted in January 2000 after the 1999 turnaround.

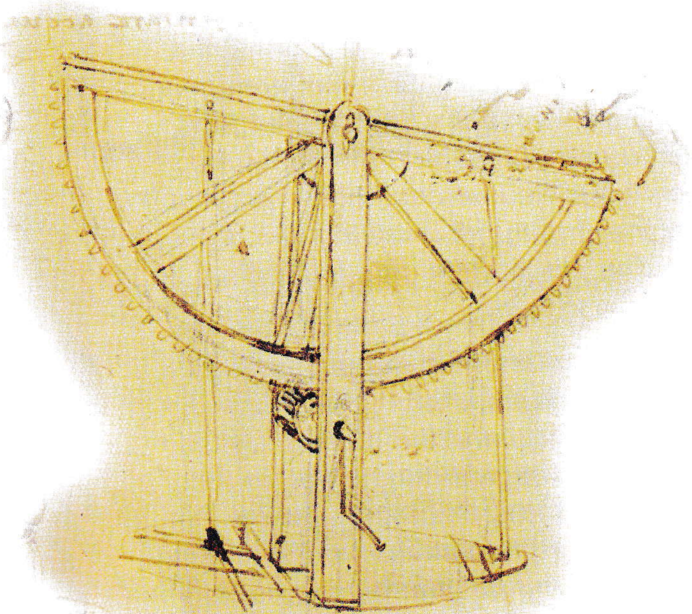


Figure 1 – Steam turbine horsepower.

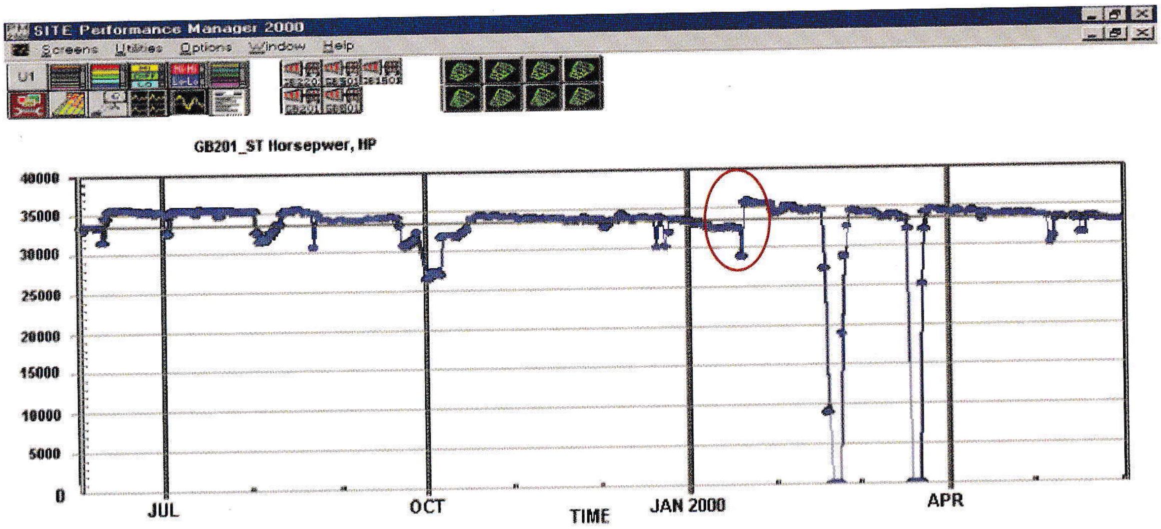


**Figure 2** – Zoom in on steam turbine horsepower.

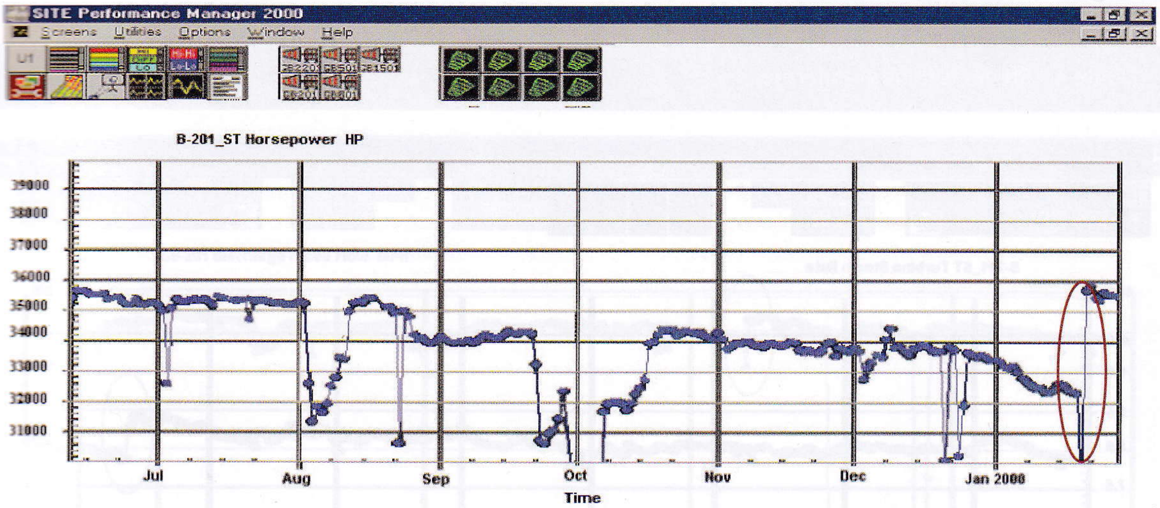
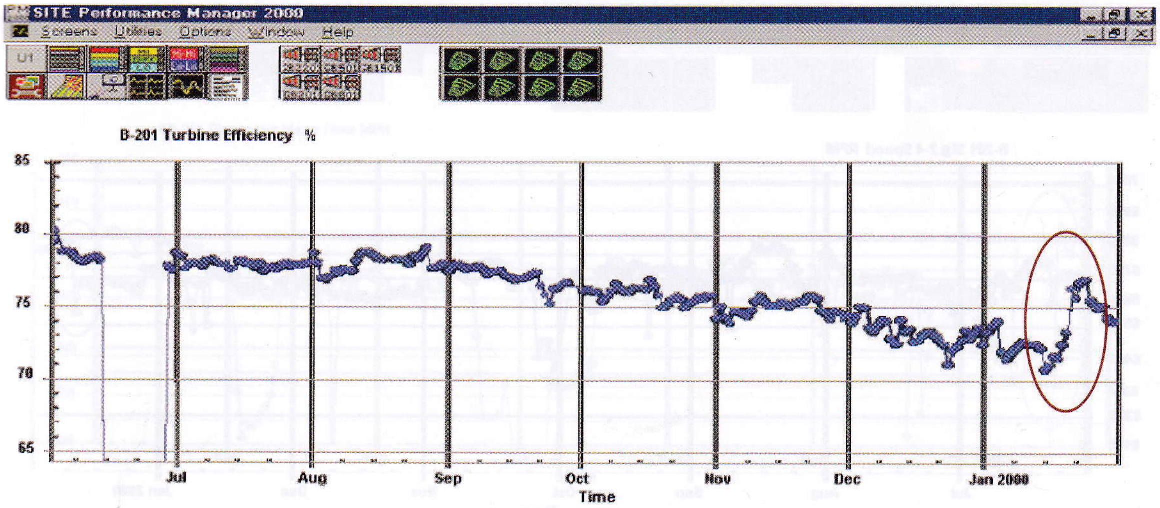
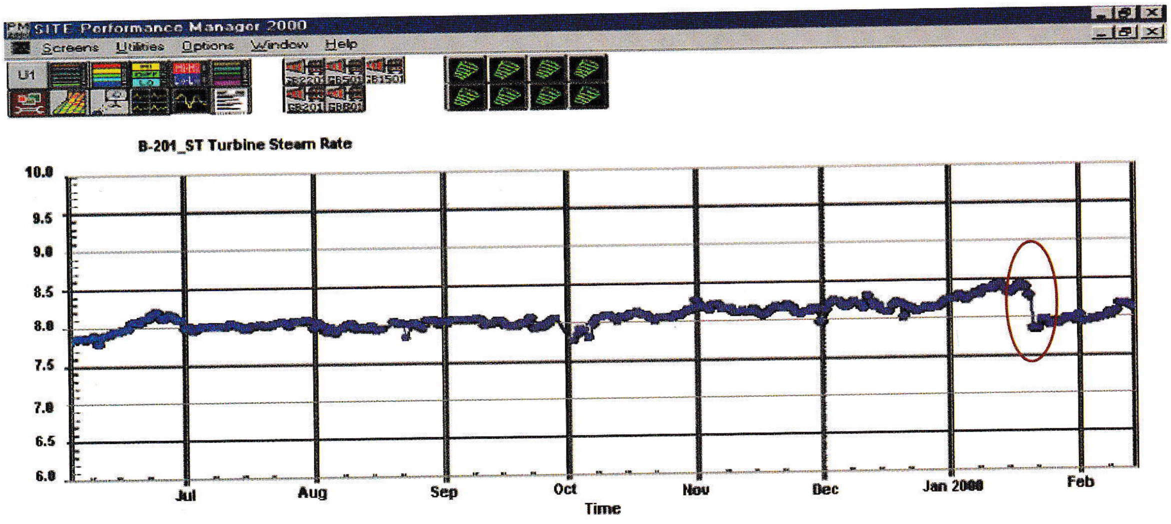


Figure 3 – Steam turbine efficiency.



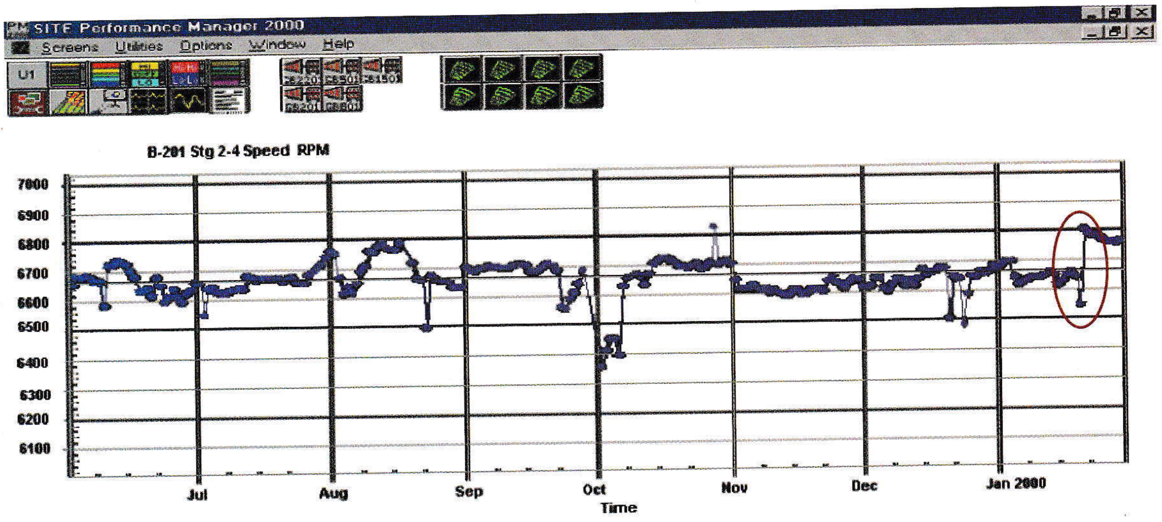
The effect of the fouling in the steam turbine was a 10% loss in efficiency that was practically reclaimed after the January 2000 online water wash (Figure 3), and an increased demand in steam that was reduced by the online water wash (Figure 4).

Figure 4 – Steam turbine steam rate.



The effects of the fouling on the ethylene production are seen in Figures 5-7. First, the degradation in steam turbine efficiency and increased steam rate was having a detrimental effect on machine train speed, and a 300 RPM increase was achieved in the high-speed section of the machine train after the online water wash (Figure 5).

Figure 5 – Charge gas compressor 2nd–4th stage speed.



This speed change resulted in a recovery of the lost mass flow due to the steam turbine fouling effects on operation. Figure 6 reflects the change in mass flow after the 1999 turnaround until the January 2000 online water wash of the steam turbine.

Figure 6 – Charge gas discharge mass flow.

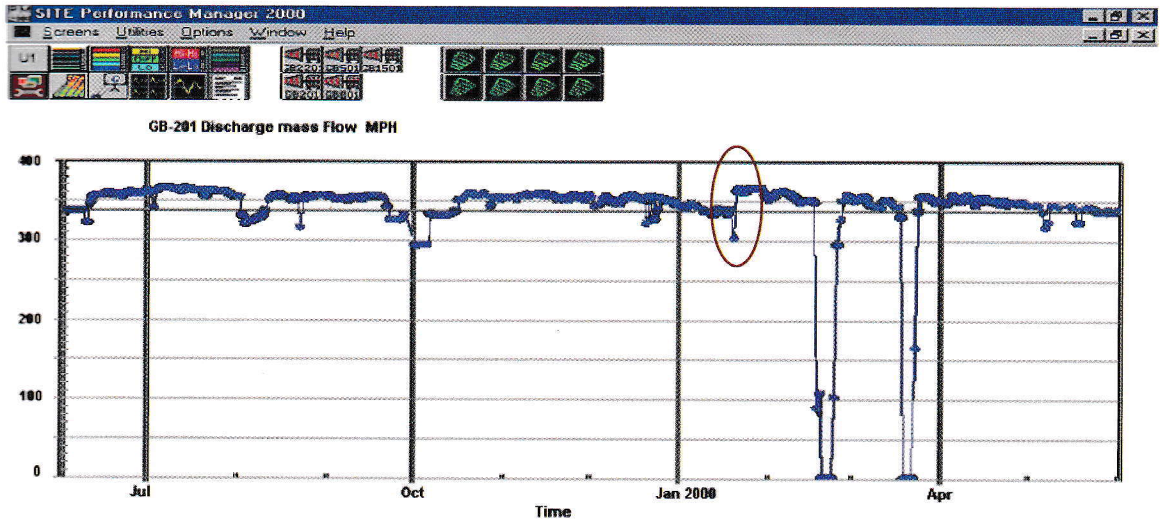
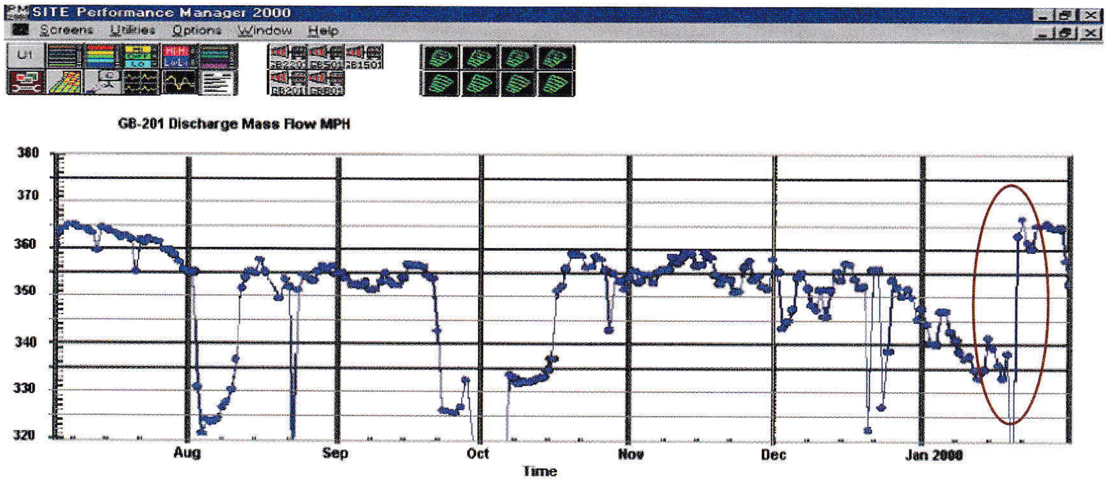


Figure 7 is a shorter timeframe of Figure 6 showing the discharge flow decreasing from 365,000 lbs/hr to 335,000 lbs/hr. The online water wash performed in January 2000 returned the mass flow to 365,000 lbs/hr.

Figure 7 – Zoom in on discharge mass flow.



As with any procedure, online water washes need to be evaluated using a cost/benefit analysis. Costs are usually in the form of lower plant rates in order to minimize thrust loads on the turbine, while the benefits can be the increase in product throughput. The plant conducted a cost/benefit analysis to determine the optimum frequency to manage their costs versus recovery gains in production rates. Careful analysis such as this can enhance the plant's bottom line as risk factors such as stress on machines and production losses are managed. Having the right information—in this case performance data—and placing all the pieces of the puzzle in their complex orders, can provide a clearer picture of overall plant profitability.

## Vibration Monitoring with Performance Monitoring

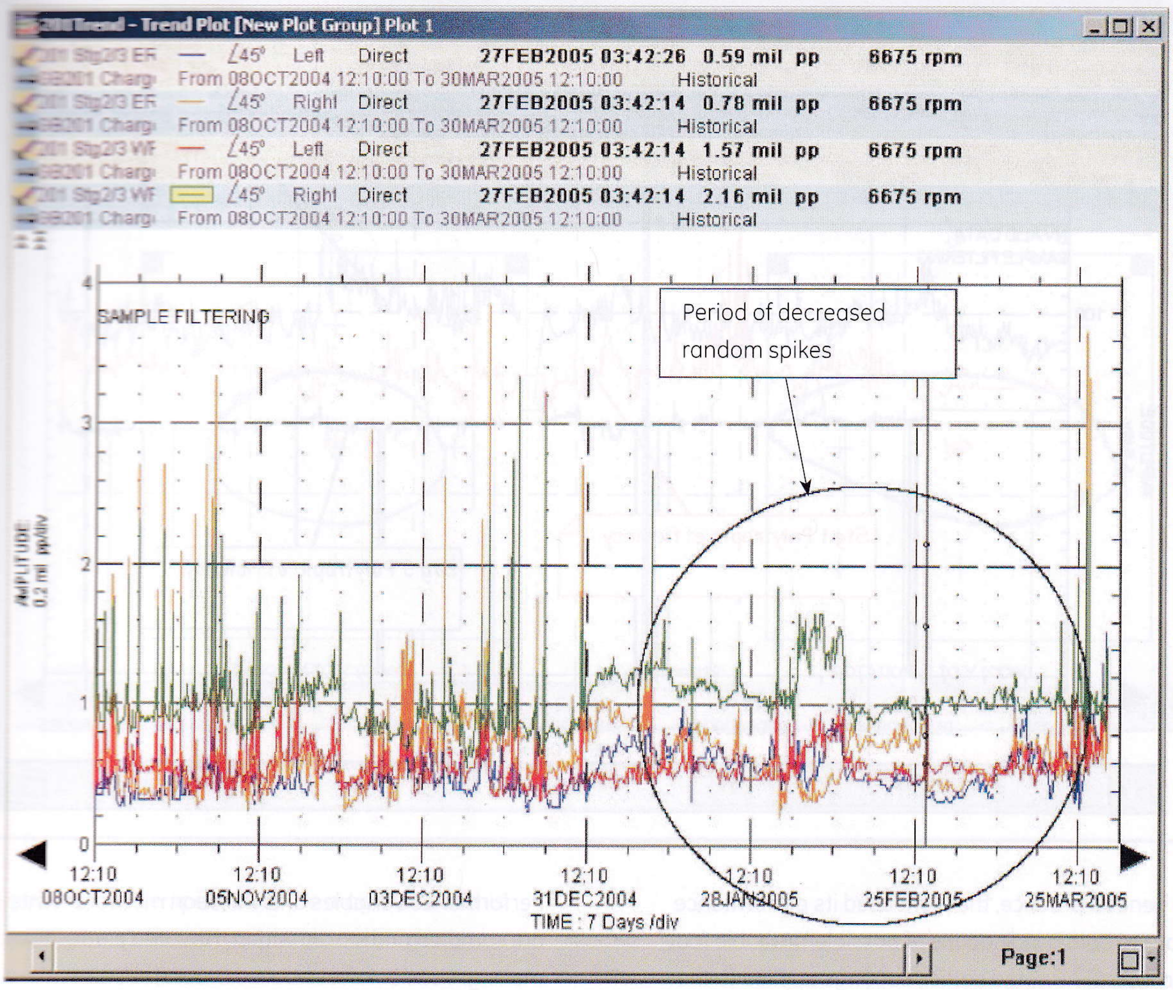
DuPont SRW transitioned its vibration monitoring platform to System 1® optimization and diagnostic software. System 1 incorporates the historical focus of Bently Nevada™ products on condition monitoring for rotating and reciprocating machinery by combining support for online and offline data sources. However, System 1 extends condition monitoring capabilities beyond just machinery to include other plant assets as well—assets such as vessels, piping, boilers, heat exchangers, valves, instruments, and virtually any equipment for which condition information is desired.

Additionally, the Performance Manager 2000 package was transitioned to Bently PERFORMANCE™ software. Bently PERFORMANCE extends the functionality of System 1 by adding integrated thermodynamic performance monitoring. It can be used for machinery such as gas and steam turbines, rotating and reciprocating compressors, and pumps. It can also be used for non-rotating assets such as boilers, heat exchangers, and other thermal machines. The software uses the same database and display components as System 1, resulting in a seamless, integrated system with a single user interface.

The compressor rotor coatings would contribute to a minimum eight-year period of no fouling. After eight years (1995-2003) of increased ethylene production rates, DuPont SRW evaluated plant operations and undertook efforts in 2003 to remove bottlenecks, in the expectation of increasing ethylene production even further. Ethylene production rates did increase, and the effects on performance and vibration signatures on the machines in the unit were monitored with System 1 and Bently PERFORMANCE software.

In late 2004, vibration "spikes" were noticed on the Charge Gas Compressor train; specifically, spiking appeared on the Stage 2/3 compressor which was located just after the gear box in this machine train (Figure 8).

Figure 8 – Stage 2/3 vibration trend October 2004–March 2005.



```
Trend - Trend Plot [New Plot Group] Plot 1
201 Stg2/3 ER   —  ∠45°  Left   Direct   27FEB2005 03:42:26  0.59 mil  pp   6675 rpm
SB201 Charg     From 08OCT2004 12:10:00 To 30MAR2005 12:10:00   Historical
201 Stg2/3 ER   —  ∠45°  Right  Direct   27FEB2005 03:42:14  0.78 mil  pp   6675 rpm
SB201 Charg     From 08OCT2004 12:10:00 To 30MAR2005 12:10:00   Historical
201 Stg2/3 WF   —  ∠45°  Left   Direct   27FEB2005 03:42:14  1.57 mil  pp   6675 rpm
SB201 Charg     From 08OCT2004 12:10:00 To 30MAR2005 12:10:00   Historical
201 Stg2/3 WF   ▭  ∠45°  Right  Direct   27FEB2005 03:42:14  2.16 mil  pp   6675 rpm
SB201 Charg     From 08OCT2004 12:10:00 To 30MAR2005 12:10:00   Historical
```

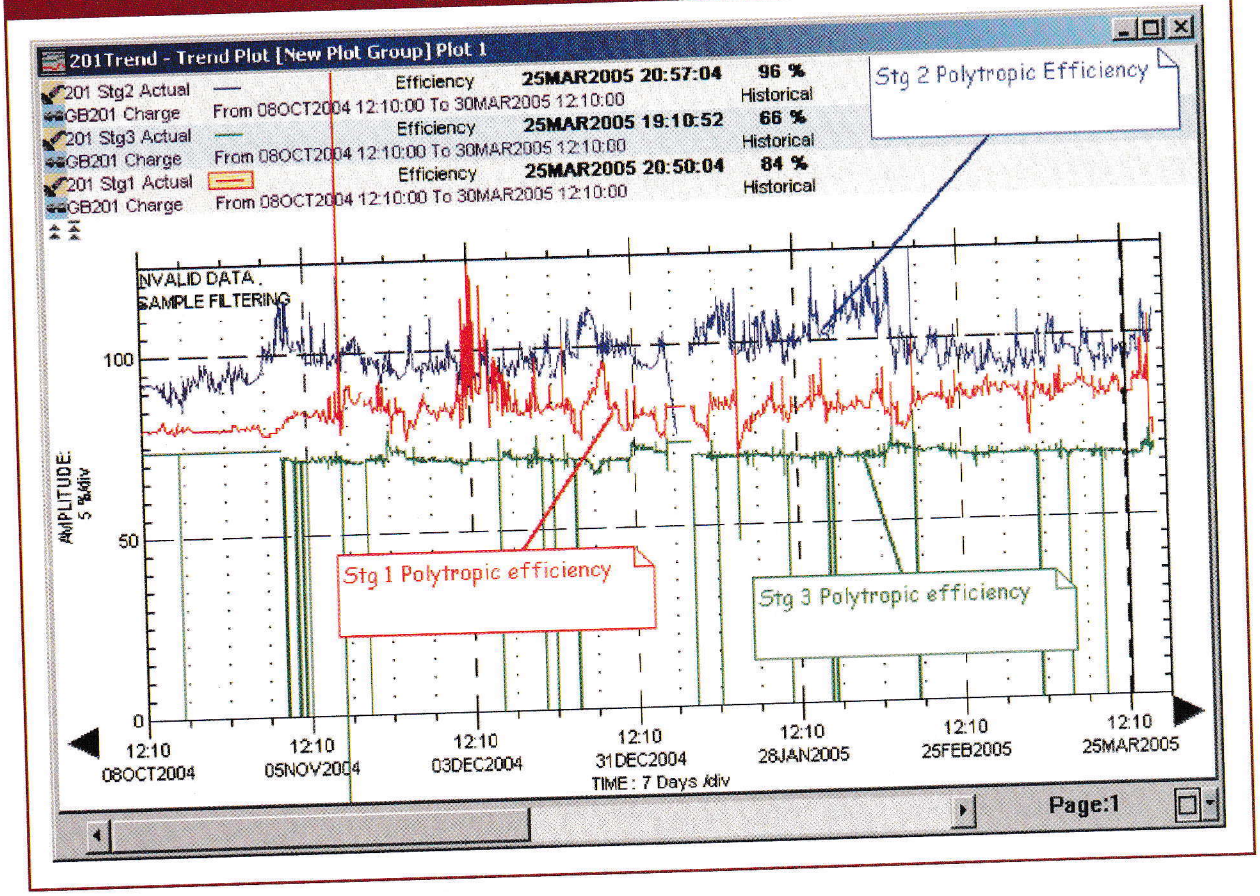


Figure 9 – Stages 1–3 polytropic efficiency October 2004–March 2005.

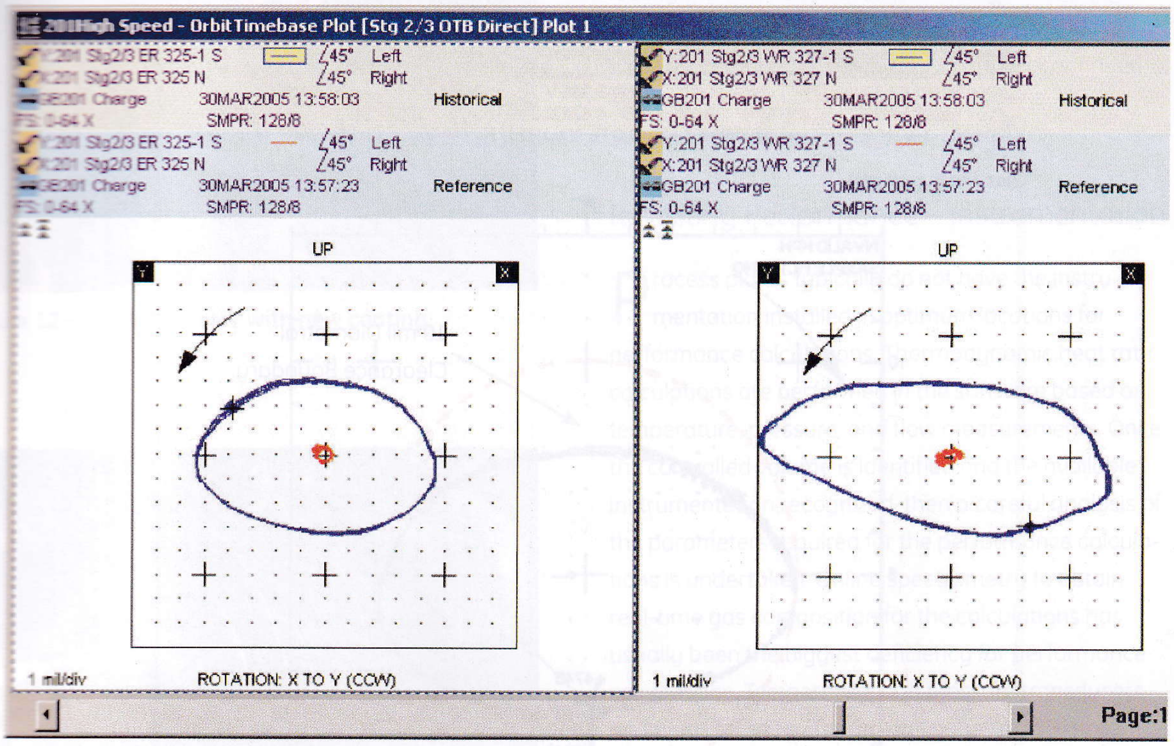
201Trend - Trend Plot [New Plot Group] Plot 1

201 Stg2 Actual — Efficiency 25MAR2005 20:57:04 96 %
GB201 Charge From 08OCT2004 12:10:00 To 30MAR2005 12:10:00 Historical
201 Stg3 Actual — Efficiency 25MAR2005 19:10:52 66 %
GB201 Charge From 08OCT2004 12:10:00 To 30MAR2005 12:10:00 Historical
201 Stg1 Actual Efficiency 25MAR2005 20:50:04 84 %
GB201 Charge From 08OCT2004 12:10:00 To 30MAR2005 12:10:00 Historical

In general practice, the plant used its performance data to obtain indications of possible/probable fouling issues. As noted earlier, coatings applied to the compressor rotors had already resulted in reduced fouling indicators, but, after the 2003 turnaround and debottlenecking effort, higher mass flow rates were seen in the compressors. Figure 9 reflects the trend in efficiency for the first three stages of the Charge Gas Compressor train, and it was noted that Stage 2 efficiency would routinely go over 100%. A review of the data and calculations revealed that one of the possible causes might be liquid carry-over, as the plant has recognized that polytropic head trends have been the dominant indicator of potential fouling issues.

Performance variables and vibration measurements are sampled and stored within the same platform, making it easier to associate vibration events with performance changes and vice versa. However, sudden vibration events may be too quick to show up on the performance trends. On 30 March 2005, a vibration spike on the Stage 2/3 compressor bearings resulted in a unit shutdown. The vibration and process data was reviewed to determine the root cause of the vibration spike. Vibration levels had been running consistently less than 2.5 mil pp on both bearings when an event occurred that caused the vibration to exceed 10 mil pp. The interlocks worked and shut the machine train down. The small Orbits in the center of each plot in Figure 10 were collected just 40 seconds prior to the larger Orbits in the two plots.

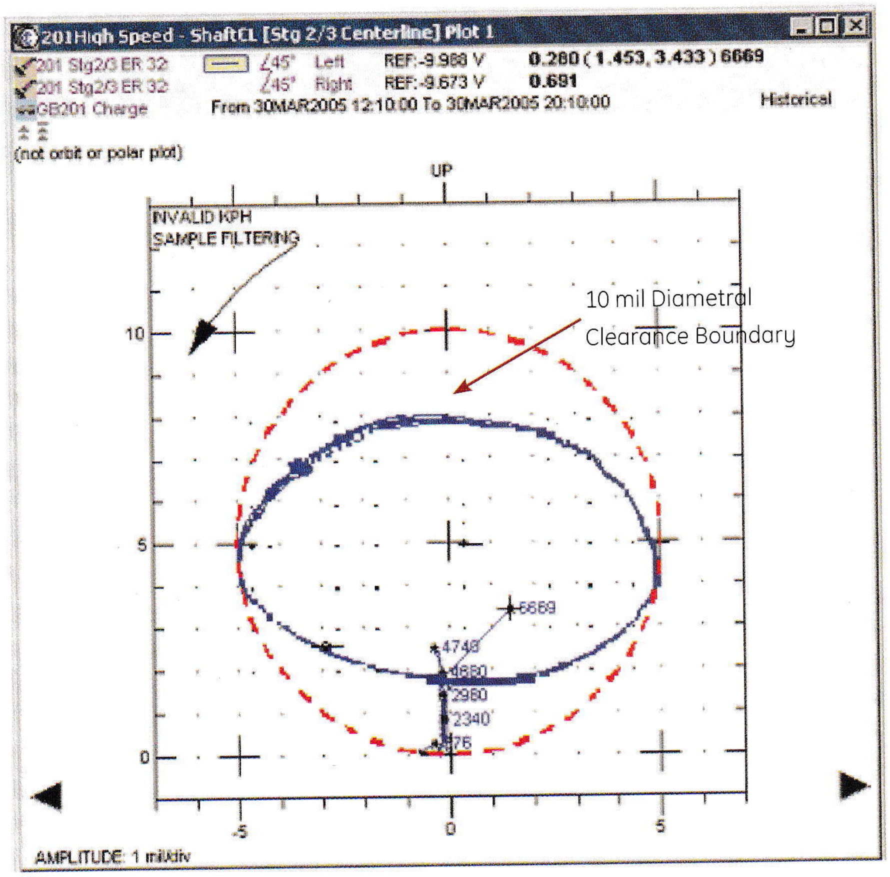
Figure 10 – Orbits at stage 2/3 compressor bearings.


201High Speed - Orbit Timebase Plot [Stg 2/3 OTB Direct] Plot 1
Y:201 Stg2/3 ER 325-1 S ∠45° Left
X:201 Stg2/3 ER 325 N ∠45° Right
GB201 Charge 30MAR2005 13:58:03 Historical
FS: 0-64 X SMPR: 128/8
Y:201 Stg2/3 ER 325-1 S ∠45° Left
X:201 Stg2/3 ER 325 N ∠45° Right
GB201 Charge 30MAR2005 13:57:23 Reference
FS: 0-64 X SMPR: 128/8
UP
Y
X
1 mil/div
ROTATION: X TO Y (CCW)
Y:201 Stg2/3 WR 327-1 S ∠45° Left
X:201 Stg2/3 WR 327 N ∠45° Right
GB201 Charge 30MAR2005 13:58:03 Historical
FS: 0-64 X SMPR: 128/8
Y:201 Stg2/3 WR 327-1 S ∠45° Left
X:201 Stg2/3 WR 327 N ∠45° Right
GB201 Charge 30MAR2005 13:57:23 Reference
FS: 0-64 X SMPR: 128/8
UP
Y
X
1 mil/div
ROTATION: X TO Y (CCW)
Page:1

To get another perspective of the magnitude of this spike, Figure 11 shows the inboard bearing Orbit superimposed onto the shaft centerline plot. It can be plainly seen that the size of the Orbit was restricted by the bearing clearance.

> “Monitoring the vibration and performance parameters enabled the plant to make informed decisions for their continued success and productivity.”

Figure 11 – Stage 2/3 inboard bearing.



The plant engineering group reviewed the performance and vibration data and determined that the unit could be restarted without any need for further inspection, but they did monitor the data closely for potential developments. The unit ran for two more months before the vibration spiked high enough to cause a shutdown. Plans had been made for an online wash cycle, as fouling appeared to be the culprit in the random vibration spike that kept appearing after the shutdown on 30 March 2005. A brief turnaround was initiated to inspect the rotors in this train. Figure 12 shows the Stage 2/3 Rotor with a fresh, clean coating applied specifically to restrict fouling. Figures 13 and 14 show the effects of fouling from the higher rates after the 2003 turnaround.

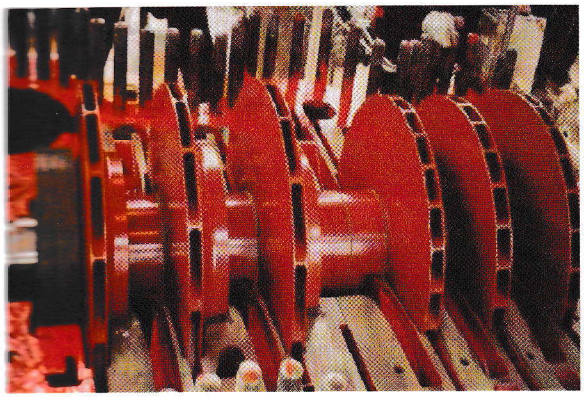


Figure 12 – Stage 2/3 rotor with new coating.

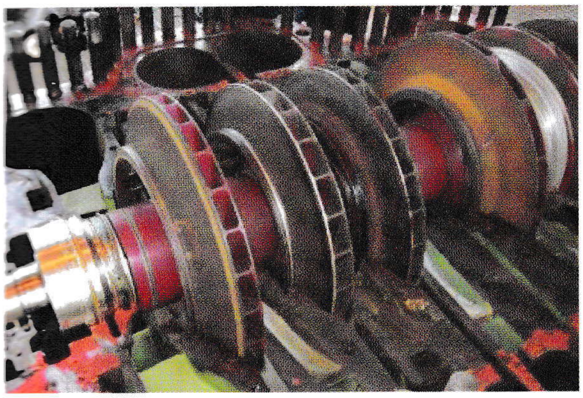


Figure 13 – Stage 2/3 rotor fouling and rub marks.

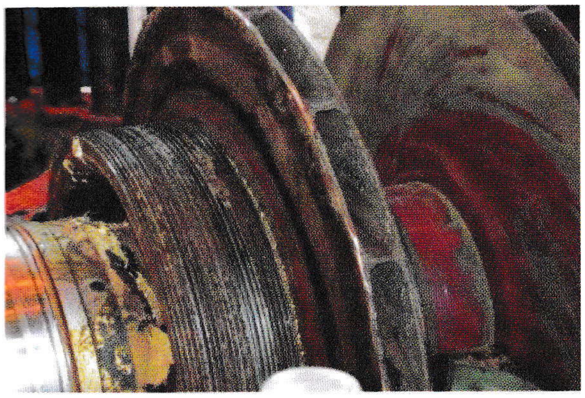


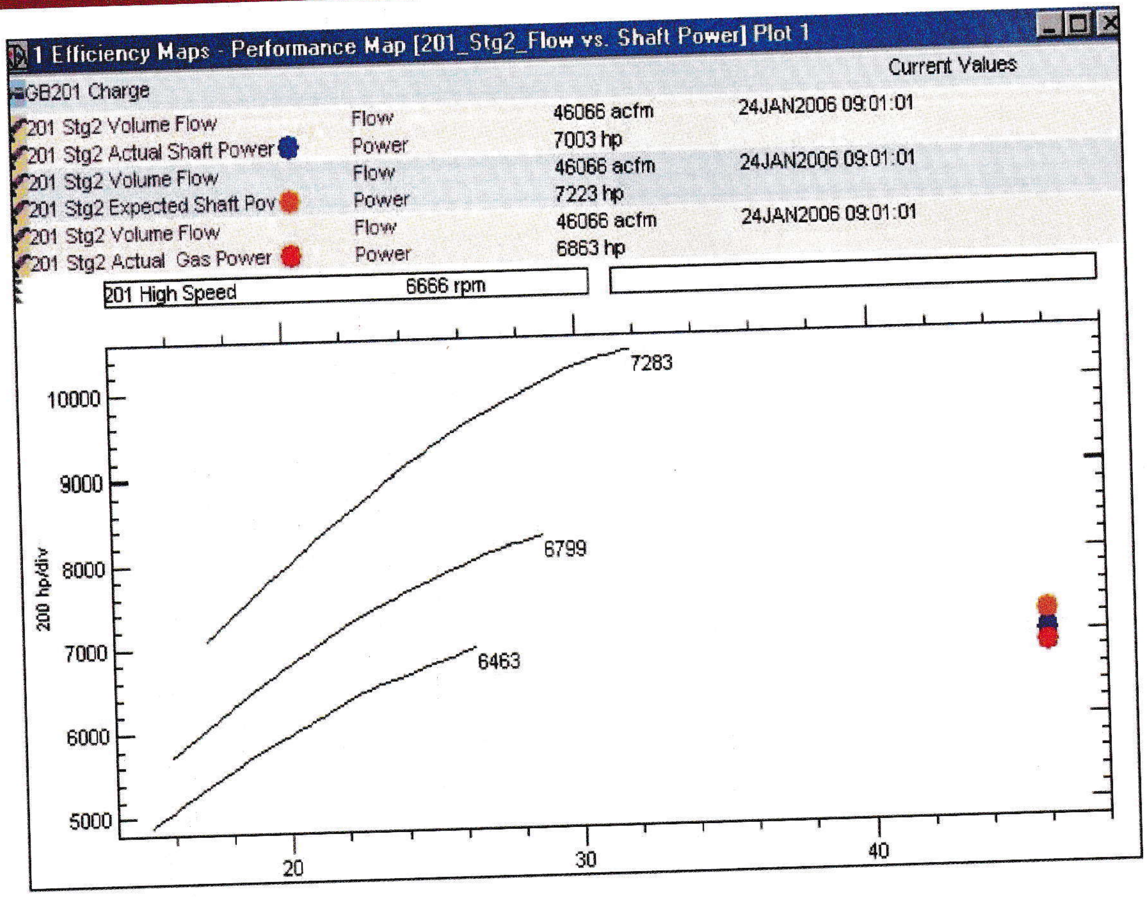
Figure 14 – Stage 2/3 rotor close-up.

Higher run rates resulted from the 2003 outage, but they also resulted in more carry-over and subsequent fouling than had been seen previously. Monitoring the vibration and performance parameters enabled the plant to make informed decisions for their continued success and productivity.

## Revisiting Performance – Instrumentation

Process plants typically do not have the instrumentation installed in optimum locations for performance calculations. Thermodynamic heat rate calculations are performed in the software based on temperature, pressure, and flow measurements. Once the controlled volume is identified and the available instrumentation recognized, then a careful analysis of the parameters required for the performance calculations is undertaken. Online spectrometry to obtain real-time gas composition for the calculations has usually been the biggest deficiency for performance calculations. Temperature and pressure transducers and flow metering instruments generally are not present at all the inlets and outlets of each required controlled volume. However, once identified, necessary instrumentation can be added to the machines to get reliable performance calculations. Additionally, the compressor manufacturer's performance curves need to be obtained so that expected and actual performance values can be plotted to ensure calculations are good and that the compressor is delivering performance it was designed to provide. These performance curves can be loaded into the Bently PERFORMANCE software.

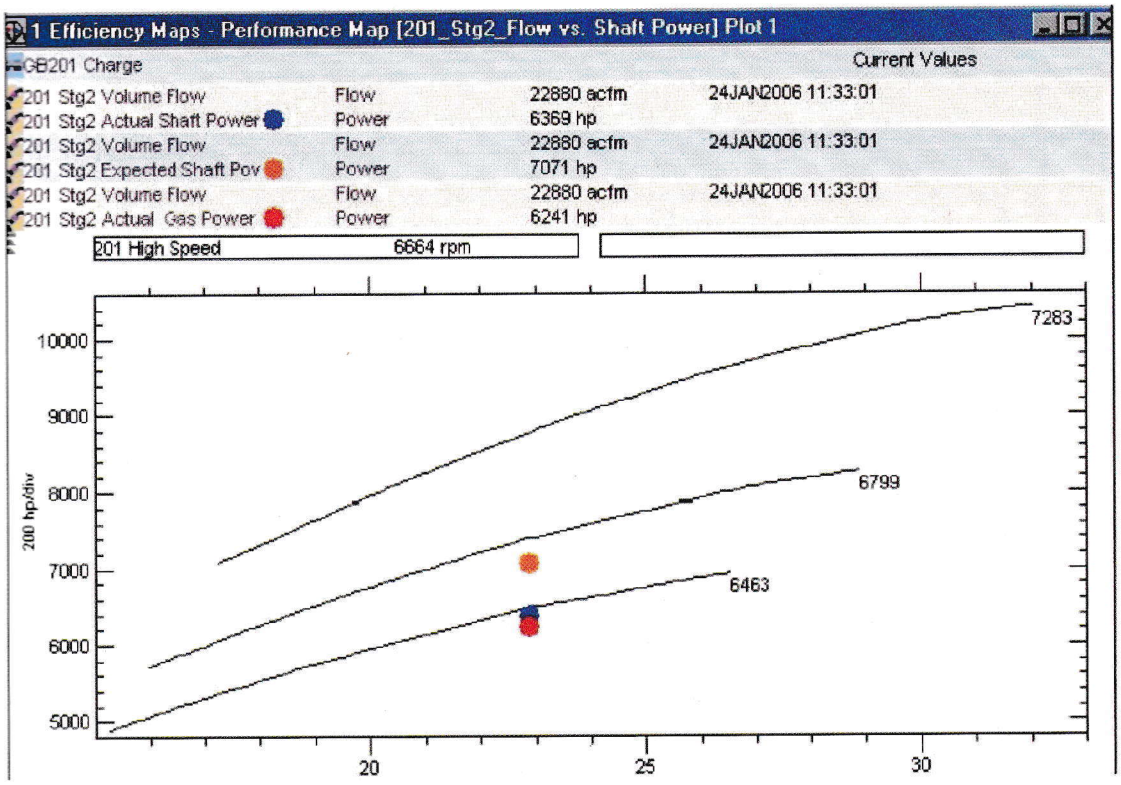
Figure 15 – Compressor map – power – wrong data.


1 Efficiency Maps - Performance Map [201_Stg2_Flow vs. Shaft Power] Plot 1
7283
6799
6463
10000
9000
8000
7000
6000
5000
200 hp/div
20
30
40

```
GB201 Charge                                                          Current Values
201 Stg2 Volume Flow             Flow     46066 acfm     24JAN2006 09:01:01
201 Stg2 Actual Shaft Power ●    Power    7003 hp
201 Stg2 Volume Flow             Flow     46066 acfm     24JAN2006 09:01:01
201 Stg2 Expected Shaft Pov ●    Power    7223 hp
201 Stg2 Volume Flow             Flow     46066 acfm     24JAN2006 09:01:01
201 Stg2 Actual  Gas Power ●     Power    6863 hp
201 High Speed                  6666 rpm
```

Once the curves are loaded into the software and the performance curve is created for the plotting of the desired value, a sanity check then needs to be performed to ensure the correct data is being sent to the calculations and back to the display. If data is plotted on the performance curve that is significantly outside the manufacturer's provided curves (Figure 15), then an evaluation as to whether the data is correct needs to be conducted. In this example, the Dynamic Data Exchange Share (DDEShare) that was created was calling the data for an incorrect stage, and the DDEShare was easily corrected (Figure 16). Typical performance calculations—Polytropic Head, Polytropic Efficiency, Power, Volume Flow, Expected Discharge Pressure, etc. —can be plotted on the performance curves to evaluate the manufacturer's expectations versus actual measurements.

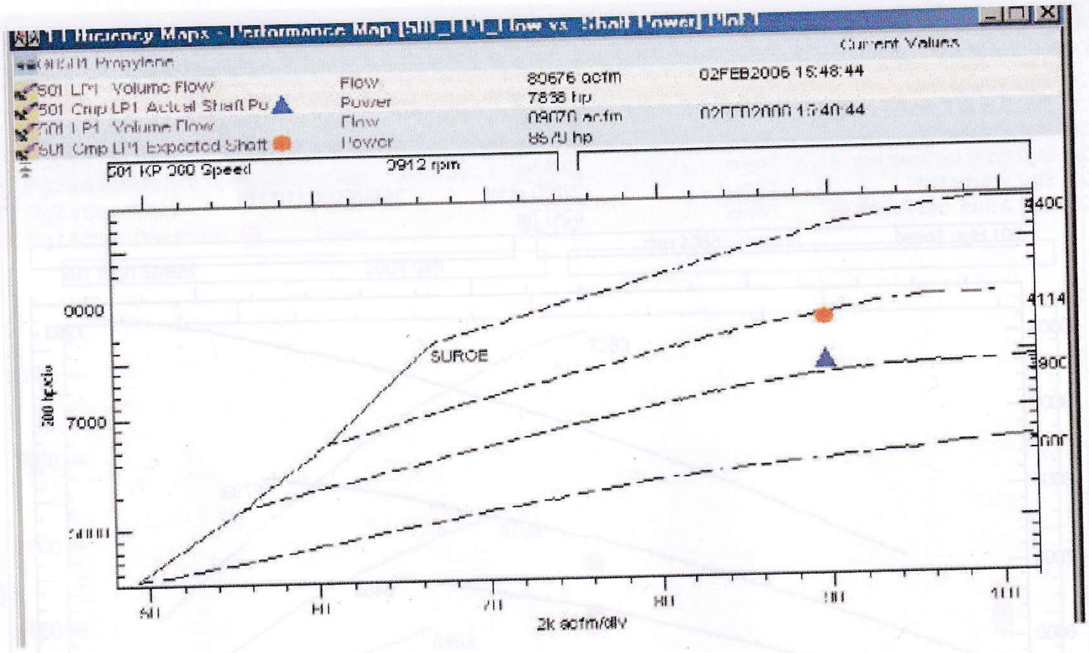
Figure 16 – Shaft power corrected values.



```
1 Efficiency Maps - Performance Map [201_Stg2_Flow vs. Shaft Power] Plot 1
GB201 Charge                                                    Current Values
201 Stg2 Volume Flow              Flow     22880 acfm    24JAN2006 11:33:01
201 Stg2 Actual Shaft Power ●     Power    6369 hp
201 Stg2 Volume Flow              Flow     22880 acfm    24JAN2006 11:33:01
201 Stg2 Expected Shaft Pov ●     Power    7071 hp
201 Stg2 Volume Flow              Flow     22880 acfm    24JAN2006 11:33:01
201 Stg2 Actual Gas Power ●       Power    6241 hp
        201 High Speed      6664 rpm
```

Figures 17, 18, and 19 show some of the additional plots available with Bently PERFORMANCE and System 1 software. When the compressor manufacturer provides the surge line, this can be included in the compressor map. The compressor maps then allow the plant to view how close they are operating to any critical points and have an idea for their stability margin. Gaps between expected and actual values should be investigated. They are usually the result of errors associated with the transducer locations and can be accounted for through modifications to the formulae calculations. Changes in the difference between actual and expected performance variables can be trended through the use of Decision Support$^{SM}$ software through custom rules development providing more tools for any plant's condition monitoring program.

## Figure 17 – Compressor map – power.



1 Efficiency Maps - Performance Map [501_LP1_Flow vs. Shaft Power] Plot 1

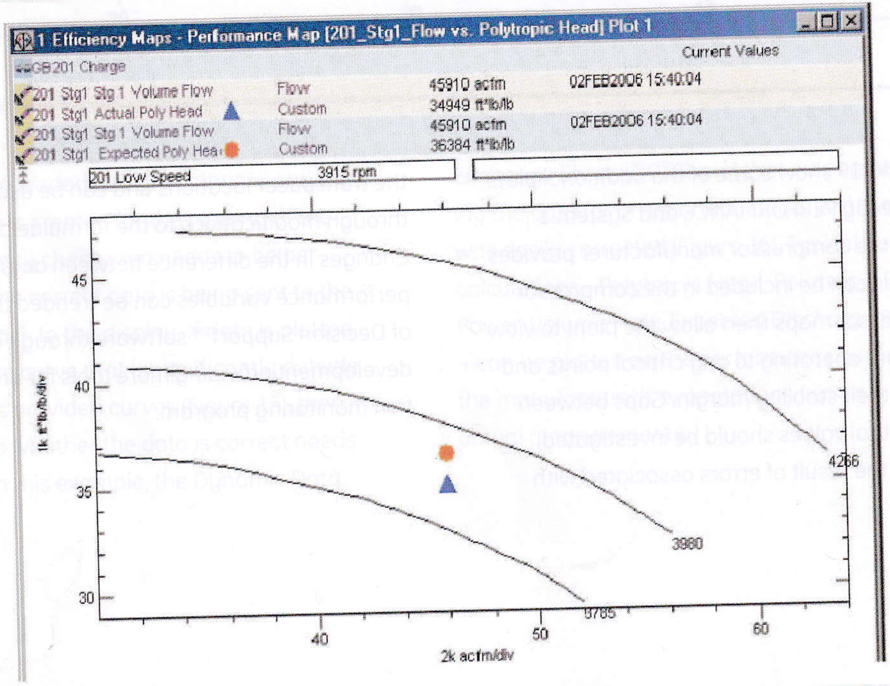
Current Values

0501 Propylene

501 LP1 Volume Flow Flow 80676 acfm 02FEB2006 15:48:44
501 Cmp LP1 Actual Shaft Pu ▲ Power 7838 hp
501 LP1 Volume Flow Flow 09070 acfm 02FEB2006 15:40:44
501 Cmp LP1 Expected Shaft ● Power 8579 hp

501 KP 300 Speed 3912 rpm

## Figure 18 – Compressor map – polytropic head.



1 Efficiency Maps - Performance Map [201_Stg1_Flow vs. Polytropic Head] Plot 1

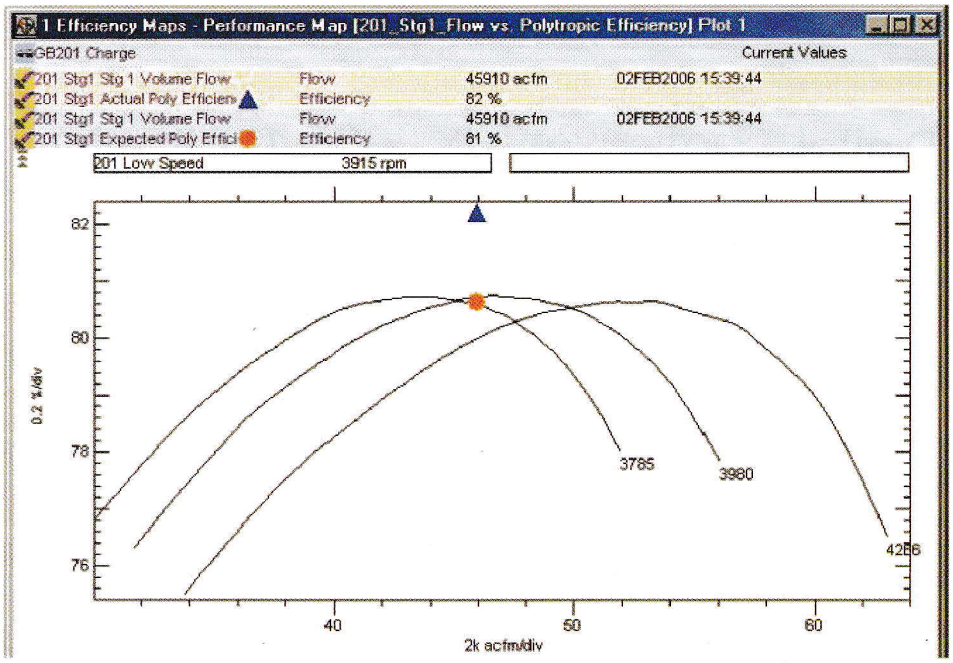
Current Values

GB201 Charge

201 Stg1 Stg 1 Volume Flow Flow 45910 acfm 02FEB2006 15:40:04
201 Stg1 Actual Poly Head ▲ Custom 34949 ft*lb/lb
201 Stg1 Stg 1 Volume Flow Flow 45910 acfm 02FEB2006 15:40:04
201 Stg1 Expected Poly Hea ● Custom 36384 ft*lb/lb

201 Low Speed 3915 rpm

Figure 19 – Compressor map – polytropic efficiency.



1 Efficiency Maps - Performance Map [201_Stg1_Flow vs. Polytropic Efficiency] Plot 1

GB201 Charge — Current Values

```
201 Stg1 Stg 1 Volume Flow        Flow         45910 acfm    02FEB2006 15:39:44
201 Stg1 Actual Poly Efficien ▲   Efficiency   82 %
201 Stg1 Stg 1 Volume Flow        Flow         45910 acfm    02FEB2006 15:39:44
201 Stg1 Expected Poly Effici ●   Efficiency   81 %
201 Low Speed                     3915 rpm
```

## Conclusion

While vibration monitoring is an important part of any condition monitoring program, integrating it with online performance monitoring can provide considerable additional value. Some of the critical measurements required for performance monitoring—temperature, pressure, flow—may need to be added to the instrument base, as the requisite transducers installed at optimum locations might be hard to find in established processing plants built over 20 years ago. While the composite accuracy of these instruments will affect any performance calculation, when the data is available and properly correlated, plants have more insight into the operational risks and can deliver refined decisions for continued operations in the wake of events. Machine inspection after an unplanned shutdown incurs major cost, not only in lost production, but also in possible liability damages as a result of contractual product delivery schedules. With data and information in the appropriate trained hands, some inspections could be avoided and cost savings immediately recognized.

Editor's Note: This case history was originally presented at the AIChE Spring National Meeting, Ethylene Producers Conference, Orlando, Florida, April 2006. The author gratefully acknowledges the assistance from Alan L Dougherty and John R. Dugas, both of DuPont Sabine River Works. Plots, analysis, and photos are courtesy of, and used with permission of, DuPont Sabine River Works.

[1] Steam Turbine Fouling, John R. Dugas, Session 92, 2002 AIChE Spring National Meeting

6 ORBIT
ailable
Sensor
ximitor®
t
ochure
n Package
asheet
act Sheet
hure
g Schedule
ting
775.215.2864

# New Product Showcase

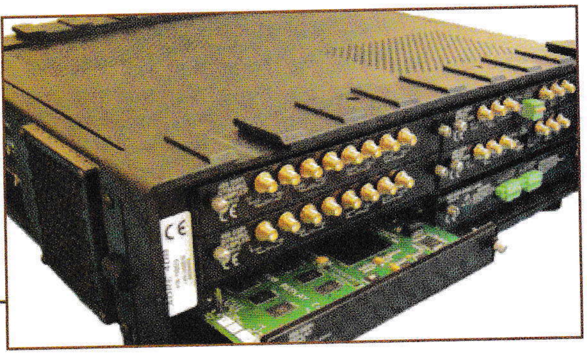
## ADRE® Digital Replay Card

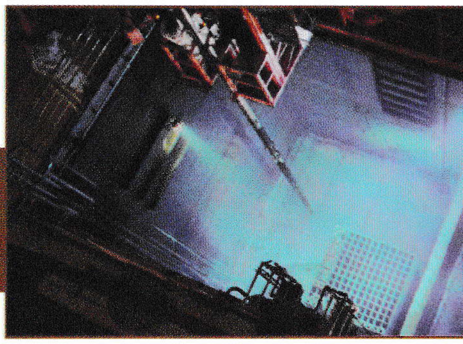
### Save time and money while eliminating data collection and analysis hassles

GE Energy's popular Bently Nevada™ ADRE® Sxp & 408 Dynamic Signal Processing instrument (DSPi) now provide the ability to replay and reprocess real-time, raw continuous data with far better precision and accuracy than other digital or analog recording instruments. This highly integrated, portable diagnostic platform reduces overall capital investment and continues to deliver as a "high-value" solution that meets customer needs in diverse industries and applications. The new Digital Replay Card offers customers more flexibility to investigate and solve problems faster and easier, create baseline data, optimize sampling criteria, filtering and triggering, and enable better presentation of data. Additionally, the card uses the 408's accessory card bay so there is no loss of either dynamic or speed channel density—keep all the channels you need while adding new functionality.

The Digital Replay Card provides the ability for simultaneous synchronous and asynchronous internal digital reprocessing and playback of all 408 DSPi channels. Exceptional accuracy and precision are maintained as part of the reprocessing functionality, far surpassing capabilities of other equipment and reprocessing techniques. The card will play back raw data for all channels simultaneously, including Keyphasor®/speed and dynamic sampler inputs. All sampling parameters can be modified on a KPH (Keyphasor) channel when replayed. KPH signals can be fully managed and re-conditioned, including gain, inversion, clamping, etc. This provides the ability to control triggering edges and thresholds as needed for reprocessing and analysis. On standard dynamic channels, most sampling parameters can be modified. As an example, waveform assignments, variable generation, filtering options, frequency span, and KPH assignments that were non-existent in the original configuration may be added/modified when the data is reprocessed. Additionally, all sampling criteria and triggering parameters may be added and modified.

Here's a scenario to consider. Suppose you want to capture machine data but are not certain what frequency ranges would be most suitable. In the past, you would have had to make an "informed guess" and then go ahead and collect the machine data—perhaps you were right, but often you could be wrong. If you were wrong, you would have to revisit the machine and collect new data. Now, with the new Digital Replay Card, you can stream the machine data directly to disk, bring the data back to your location, and reprocess the data at whatever frequency ranges, sampling ranges, or Keyphasor assignments are appropriate based on the machine knowledge you acquire. Data analysis is really only limited by your imagination—the data is there regardless of how you want to reprocess it later. Learn more at www.ge-energy.com/adre or by contacting your nearest sales professional.





# Radiation Resistant 3300 XL Proximitor® and 330530 Velomitor® Piezo-velocity Sensor

## Nuclear-rated machinery protection and condition monitoring

Operations and maintenance personnel in nuclear plants around the world rely on GE Energy's Bently Nevada™ sensors for robust, accurate machinery measurements. We have two new nuclear-rated sensor offerings that build on the experience we have gained from decades of diverse machinery monitoring and protection applications, including in demanding nuclear environments. Specifically designed and tested for monitoring pumps, motors, and other rotating machinery in harsh Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) nuclear radiation environments, both are key components for identifying changes in bearing condition, rotor unbalance, and misalignment, all of which can result in machine damage, plant safety issues, and associated costs.

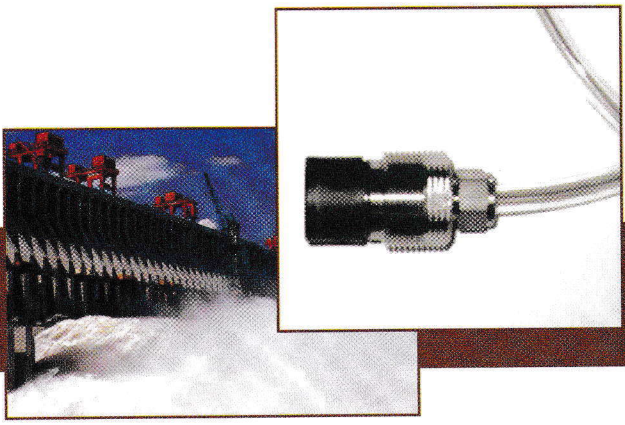
For proximity measurements, our Radiation Resistant 3300 XL Proximitor offers industry-leading technology and is part of a system specifically designed for nuclear radiation environments. The Proximitor is part of a complete system that includes existing cable 27490 and existing probes 27482, 27485, 36446, 36447 or 36448. Systems are available with an integrated probe/cable option. The system is ideal for capturing XY radial and axial vibration measurements. There are two new Proximitors—330280 (0.300) supports system lengths of 15, 40 or 110 feet, while 330281 (0.420) supports a 15 foot system length. Both Proximitors are gamma radiation resistant up to 3 Mrads and can be optioned for either panel or DIN-rail mounting.

Bently Nevada
3300 XL .420 RADIATION RESISTANT PROXIMITOR SENSOR
Bently Nevada
3300 XL .300 RADIATION RESISTANT PROXIMITOR SENSOR

For seismic measurements, the 330530 Radiation Resistant Velomitor Sensor is also available to measure absolute (relative to free space) bearing housing, casing, or structural vibration. With similar gamma radiation resistance, this robust sensor incorporates solid-state electronics with no moving parts and will not suffer from mechanical degradation and wear. It can be mounted vertically, horizontally, or any other orientation angle.

As we're highlighting in this issue of ORBIT, the nuclear industry is experiencing a Renaissance, and both of these new products extend the Bently Nevada product line to incorporate our very latest technology to address our nuclear customers' needs. Visit us at www.ge-energy.com/rr3300xl or www.ge-energy.com/rrvelomitor for more information on these products or contact your sales professional.

NEW PRODUCT SHOWCASE



# 3300 XL Underwater Probes

## 8 mm, 11 mm, and 25 mm solutions for submerged applications

GE Energy's new Bently Nevada™ 3300 XL Underwater Probes are designed specifically for applications in harsh underwater environments. With a new watertight design, these robust, high-performance probes are ideal for use in applications where constant liquid exposure makes the installation of standard probes impossible, such as in hydroelectric plants and wastewater treatment facilities. Watertight tubing around the probe case protects the probe cable from liquid ingression and the likely failures that can result. The probes are pressure-rated to 500 PSI (34 bar), which is equivalent to 1150 feet of water!

3300 XL Underwater Probes are available in three standard tip sizes—8 mm, 11 mm, and 25 mm—and they are compatible with the corresponding standard 3300 XL Proximitors and cables. And, since the probes are part of the 3300 XL line, you can expect them to perform to the same demanding design rigors as all of our other XL systems with higher signal accuracy, better performance over temperature, more repeatability and easier installation via ClickLoc™ connectors. You can learn more about these new probes at www.ge-energy.com/underwaterprobes or from your nearest sales professional.

---

RECIP TIPS

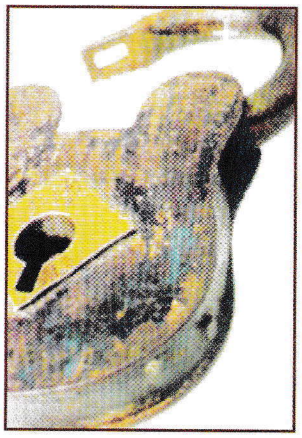
# When is Rod Drop the Right Measurement for Reciprocating Compressors?

Over 30 years, GE Energy has developed an extensive offering of proven hardware, software, and services specifically designed to address the monitoring requirements of reciprocating compressors. These include the state-of-the-art Bently Nevada™ 3500 Series machinery protection system and System 1® optimization and diagnostics software. As part of a comprehensive reciprocating compressor condition monitoring solution that includes cylinder pressure, crosshead acceleration, frame vibration, discharge temperature, and other measurements, many users have elected to include the rod drop measurement.

Is Rod Drop the Right Measurement for My Reciprocating Compressor?

Rod drop can indicate vertical piston movement inside the cylinder, calculated from the measurement of piston rod movement at the pressure packing case. However, inferring piston movement from the measurement of rod movement is based on a number of assumptions, and in some compressor configurations these assumptions are not valid. Their applicability must be evaluated on a case-by-case basis.

To help you determine whether the rod drop measurement will provide value in your specific application, we have prepared a new application note. For a copy, visit www.ge-energy.com/roddrop or contact your nearest sales professional.



GE
Energy

# Unlocking the Potential: 2007 Optimization and Control Users' Conferences

Building on our successful 2006 Users' Conferences, we're pleased to hold conferences in four key global locations in 2007, beginning with...

## Machinery Asset Management and Software Users' Conference
## Amsterdam, The Netherlands – March 13-15

Bringing together diverse users of asset condition monitoring hardware and the System 1® software platform, this conference will feature user presentations and user group breakout sessions, training, and state-of-the-art technology seminars. Designed to provide access to system experts, while facilitating sharing and networking with your peers from around the world, you'll learn about:

- Getting more from your System 1 software through powerful educational sessions with product tips and tricks
- How other users are applying their systems in new and innovative ways
- Why and how users are integrating their systems with other reliability, control, maintenance, and business applications
- The future of condition monitoring and optimization technologies

## Other Conferences Coming in 2007...

Dubai, UAE – May

Houston, Texas, USA – July

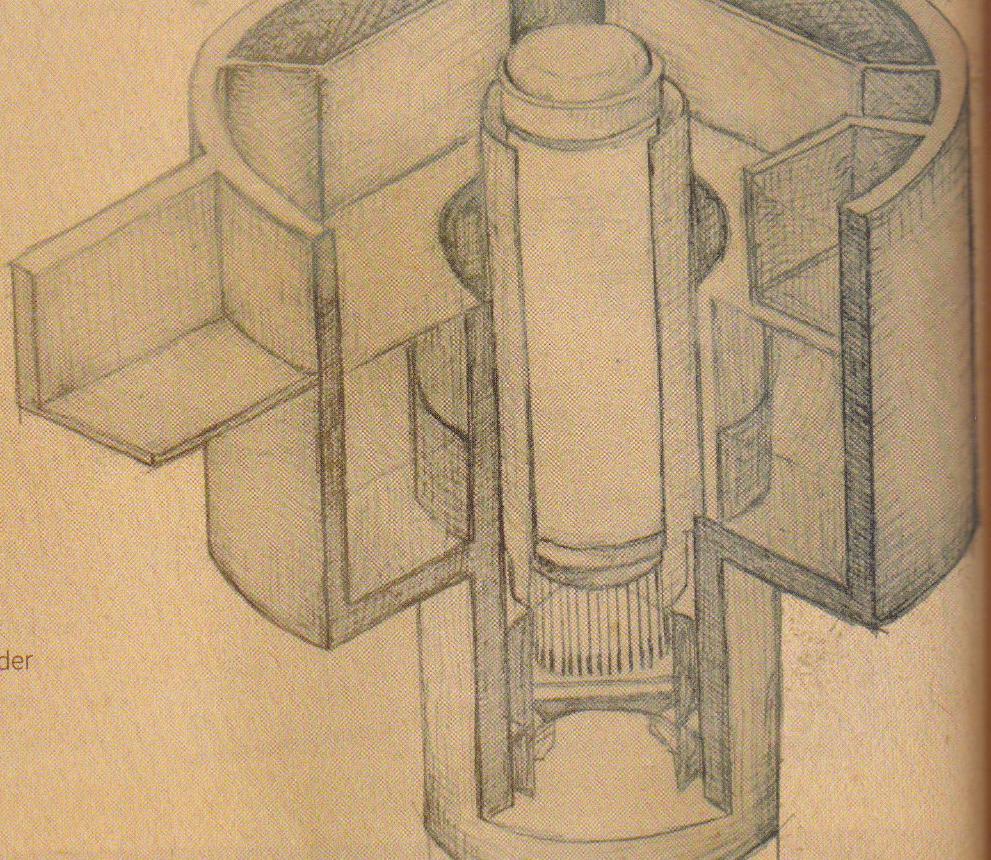
Singapore – August

Future issues of ORBIT will provide details about these events as the dates grow closer. For the very latest information on any of our 2007 conferences, visit us online at www.ge-energy.com/unlock

imagination at work

# the NEW ERA of Nuclear Power

It may seem odd to our U.S. audience that GE would dedicate an issue of ORBIT to an industry that in 1979 saw U.S. new power plant construction come to a standstill. However, nuclear power continues to mature as a significant global power generation source both in terms of new plants as well as upgrades and plant life extensions of existing facilities. This is often referred to as a new era of nuclear power—a *Nuclear Renaissance*. Also, there is a belief that new nuclear power plants will once again be built in the U.S. This article discusses the nuclear market outlook, GE's investment and commitment, and how GE is addressing various nuclear instrumentation and control challenges.



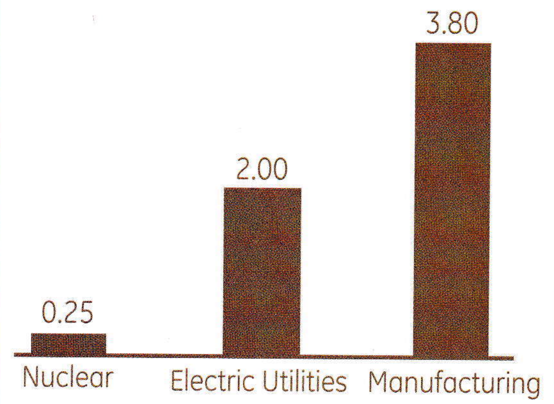
Brian Jordan
Nuclear Market Segment Leader
Optimization and Control
GE Energy
brian.jordan@ge.com

## A number of factors are driving the Nuclear Renaissance:

### Safety

Safety continues to be the number one focus with nuclear power. Safety goes beyond the importance of avoiding a nuclear incident. Attention to detail throughout operations and engineering is paramount to achieving safety. Following the Three Mile Island accident in 1979, the U.S. established the Institute of Nuclear Plant Operations (INPO) for industry collaboration on safety as well as operational performance. Additionally, owners groups such as the GE Boiling Water Reactors Owners Group (BWROG) were established. The U.S. Nuclear Regulatory Commision (NRC) specifies that reactor designs must meet a 1 in 10,000 year core damage frequency probability (the likelihood, given the way a reactor is designed and operated, an accident could cause the fuel in the reactor to be damaged; today's reactor designs significantly exceed this design requirement—GE's new Economic Simplified Boiling Water Reactor, for example, exceeds a 1 in 10 million year damage frequency probability). The overall attention to detail has led to an industrial safety accident rate as measured by 2004 U.S. Bureau of Labor Statistics that is an order of magnitude better than general industry (Figure 1)[1].

**Figure 1 – U.S. industrial safety accident rate performance.**



*Source: U.S. NRC and U.S. BLS*

### Environmental Benefit

As deep concerns of the risk and impact of global warming escalate, nuclear power is seen as one potential solution to mitigate greenhouse gas emissions from other energy sources cited as contributors. Many environmentalists, including Dr. Patrick Moore, founding member of Greenpeace and currently Chairman and Chief Scientist of Greenspirit Strategies, who were initially against nuclear, are now pro-nuclear. Dr. Moore now spends time and effort advocating the importance of nuclear energy.

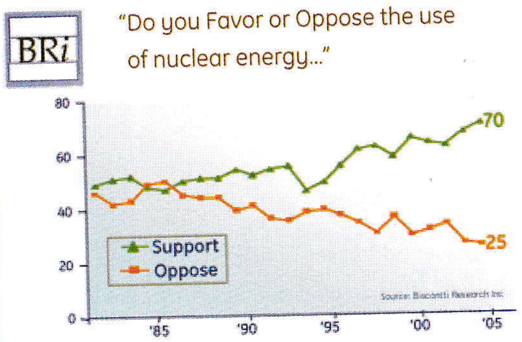
### Fuel Diversity and Cost

Nuclear power addresses concerns over fuel supply diversity (i.e., reliance on potentially unstable fuel such as oil and gas) and fuel costs. As nuclear plant technology advances, the ability to more completely use fuel will further reduce nuclear fuel cost. In the U.S., the "easy" natural gas is being consumed by industry, and the price of natural gas has increased. Additional sources of natural gas may require substantial infrastructure via exploration and production and/or liquefied natural gas receiving terminals, processing, and transportation investments. In contrast, GE estimates the nuclear fuel supply from known reserves—maintaining the current 17% worldwide share of nuclear power—to be 85 years with 2nd Generation reactors, expanding to 180 years with 3rd Generation reactors, and further expanding to 2000 years when 4th Generation multi-pass breader reactors are implemented. This does include the addition of new reserves and new fuels such as thorium. Additionally, nuclear fuel accounts for just 10-15% of the cost of power generation versus roughly 70% for a natural gas plant.

### Public Support

Public perception of nuclear power continues to improve year over year. In fact, in the U.S., more than two-thirds of the public is supportive of nuclear power according to a survey by Bisconti Research (BRi) for the Nuclear Energy Institute (NEI) (Figure 2).

**Figure 2 – U.S. public support for nuclear power growing.**



### New Build Cost and Schedule Certainty

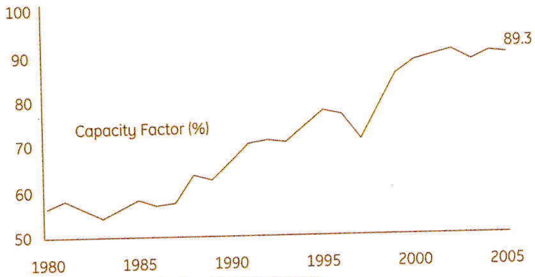
Concern about the cost and a schedule of a new power plant build is a critical consideration for potential plant owners. New plant suppliers believe that this uncertainty has been greatly reduced via a simplified and modular design, improved regulatory processes, and a positive governmental policy focus.

### Economic Operations Certainty

Strong economics for nuclear is further supported by the increasing capacity factors that have been realized over the past two decades for nuclear power plants—driving lower generation costs. The average capacity factor for operating U.S. plants in 1980 was 56.3%, in 1990 it was 66%, and in 2005 it was 89.3% (Figure 3). The U.S. Nuclear Industry is achieving record levels of performance. Globally, the unit capability factor reported by the World Association of Nuclear Operators (WANO) for 429 nuclear power plants in 2005 was 86.8%[2]. At the end of 2006, there were 442 nuclear power plants in operation with 29 new plants under construction.

Fundamentally, the economic viability of nuclear has become today's reality. For example, U.S. capacity factors in the 10 years from 1993 to 2003 produced incremental additional power equivalent to 46 new 500 MW plants! Nuclear plant operators, government, and non-government organizations have worked together over the past decades to share lessons learned and solve issues creating a safe, efficient, and reliable industry.

**Figure 3 – U.S. Nuclear Industry achieving record levels of performance.**



Source: Global Energy Decisions/Energy Information Administration

## Nuclear Proliferation and Spent Fuel Concerns

No discussion about potential nuclear power would be complete without recognizing the challenges associated with nuclear proliferation and the concerns with storing and processing spent fuel. The challenge of nuclear proliferation is an issue that the international community continues to focus on, especially with respect to the transfer of enrichment technology that could be used for military purposes. The United Nations "Atoms for Peace" International Atomic Energy Agency (IAEA) has proposed a centralized enrichment fuel bank as one potential solution. In addition, the U.S. Department of Energy Global Nuclear Energy Partnership (GNEP) initiative has goals that include: proliferation resistant recycling; converting spent nuclear fuel to usable energy; reactor technology; fuel services for global nuclear energy demand; and nuclear safeguards. Safeguard monitoring technologies and procedures continue to improve. Regarding spent fuel storing and potential processing, in the U.S. there is no current reprocessing of spent fuel, although that issue is being studied by government policy makers and may well change. Additionally, spent fuel is fully contained within fuel rods, is low in volume, and small in size, allowing for tracking and handling. Options for the optimal solution for spent fuel storage continue to be debated.

## Nuclear Investment

GE Energy is investing heavily in nuclear technology as part of its broad portfolio of power conversion technologies focused on meeting diverse global energy demands in an efficient, environmentally friendly manner, and that also includes thermal (gas and steam), wind, solar, and others. For example, GE is leveraging proven technology and nuclear plant design experience from its 3rd Generation Advanced Boiling Water Reactor (ABWR) deployed in the mid 1990s. This design has been, and continues to be, implemented in Asia (Figure 4). The ABWR technology is the foundation for the development of the Economic Simplified Boiling Water Reactor (ESBWR)—GE's latest generation of advanced nuclear power plant design. The ESBWR features passive safety systems, modular construction techniques, and modern instrumentation and control. ESBWR simplification and standardization of design greatly reduce the costs and schedule concerns of a new power plant build (Figure 5).

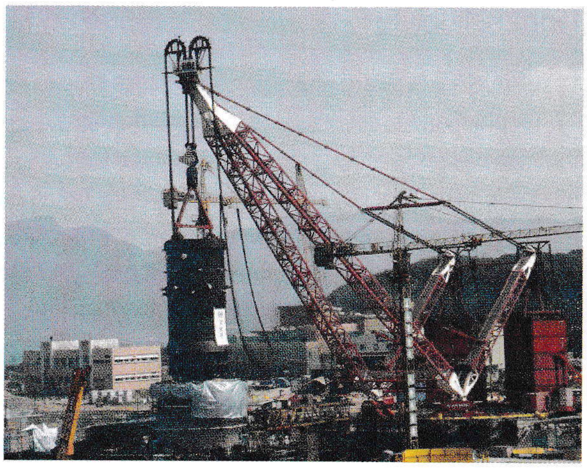


**Figure 4 – Advanced Boiler Water Reactor (ABWR) – modular construction.**

Another long-term GE Energy Nuclear investment is in fuel enrichment. In early 2006, GE completed a technology acquisition agreement for the laser isotope separation technology invented by materials technology developer Silex Systems Limited in Australia. Under this agreement, GE has the exclusive rights to develop, commercialize, and launch this third-generation uranium enrichment technology on a global basis. The laser isotope separation process is designed to be a more efficient and cost-effective production system than existing energy-intensive gaseous diffusion or capital-intensive centrifuge enrichment methods.

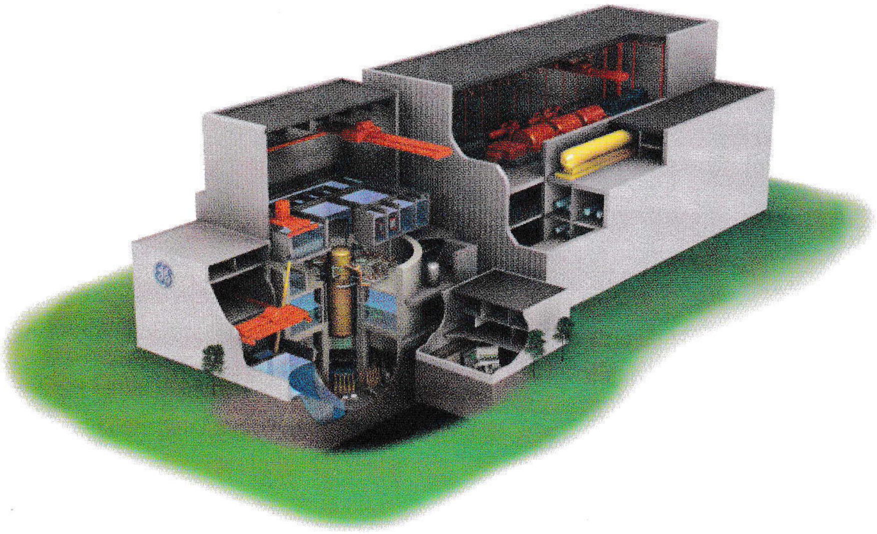


**Figure 5 – Economic Simplified Boiling Water Reactor (ESBWR) – leveraging experience and technology.**

## Plant Reliability

The nuclear industry provides notable case studies for plant and asset reliability implementations that can be used as benchmarks across industries. In a base-load nuclear power plant, keeping the plant running is of paramount importance. Downtime in one of these large plants can cost 0.5 to 1 million USD in lost revenue per day, or more. Reducing maintenance and unplanned outages, and effectively managing the time and effort associated with planned outages, all impact the bottom line. Asset condition monitoring is a key enabler of maintenance and reliability program success.

## Nuclear Instrumentation and Control (I&C) Situation

The nuclear industry currently faces equipment obsolescence challenges as the existing fleet of global operating reactors age (the global average age is now 23 years). As plant owners push forward with life extensions and power uprates, work to shorten refueling and maintenance outages, and realize capacity factors approaching or even exceeding 90%, the obsolescence challenge is compounded where plant systems need upgrades and improvements to maintain and enhance plant efficiency and performance. System upgrades such as steam turbine generators and associated I&C systems are often required for life extension and power uprates. I&C system modernization requires comprehensive knowledge and complete understanding of plant operations, nuclear system engineering, analog and digital systems, and regulatory requirements.

## I&C Issues

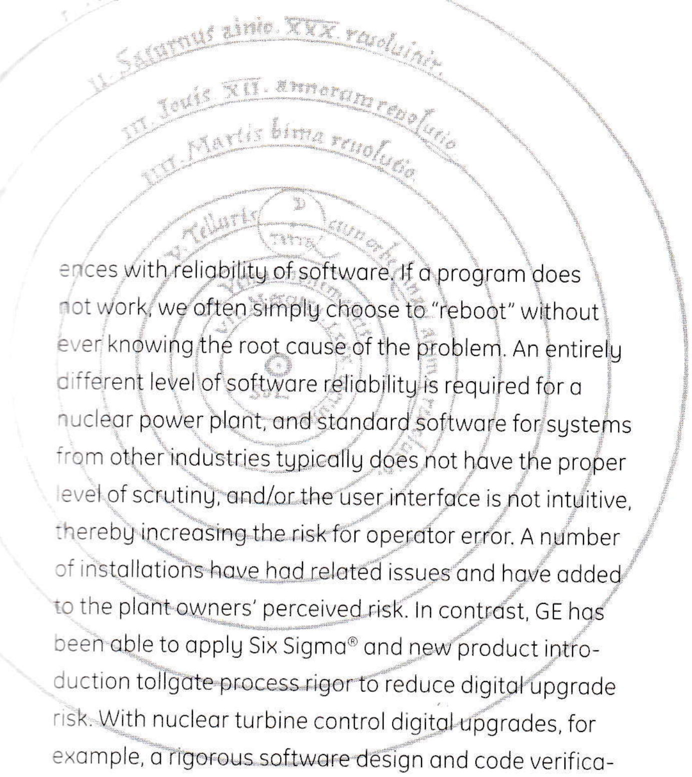
The nuclear power industry started at a time when analog control was dominant and condition monitoring was not an established discipline. Analog I&C was applied and certified for both safety and non-safety systems. As digital technology advanced, and breakthrough developments were achieved, few of these advancements made their way into nuclear power plants. Migration from analog to digital I&C required significant review, validation, education, and acceptance, as well as regulatory approval. The costs and perceived risks of a digital upgrade made migration unattractive to management.

Now, decades later, digital technology is mature and has been proven time and again in critical safety applications. The perceived risks are being mitigated by a number of successful digital control upgrade implementations, such as GE's nuclear steam turbine control upgrades. On the cost side, the maintenance of analog systems is becoming prohibitive both from a trained personnel perspective (try to find a college that still teaches analog systems) as well as an obsolete parts perspective (U.S. NRC plant licensee dialogue of plant owners searching for parts on eBay®). Amir Shahkarami, Exelon Senior Vice President, delivered the nuclear industry recommendation to the NRC at a public hearing about digital upgrades on 8 November 2006: "We believe the use of digital technology is absolutely necessary for the future of our nuclear industry. It will enhance safety. It reduces obsolescence, not only from equipment standpoint, but from a knowledge standpoint." [3]

## I&C Solutions

GE provides a full range of nuclear I&C solutions for the reactor, steam turbine generator, and balance of plant. For measuring and monitoring the nuclear reaction, Reuter Stokes Measurement Solutions instrumentation and services for both Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) power plants incorporate 50 years of experience. GE's modern reactor neutron monitoring systems address obsolescence, aging equipment, and improvements in the operator interface.

Addressing the digital upgrade perceived risk in a nuclear power plant has been and will continue to be a difficult and time consuming task. We all have experi-


II. Saturnus anno. XXX. revoluitur.
III. Iouis XII. annorum revolutio
IIII. Martis bima revolutio
V. Telluris

ences with reliability of software. If a program does not work, we often simply choose to "reboot" without ever knowing the root cause of the problem. An entirely different level of software reliability is required for a nuclear power plant, and standard software for systems from other industries typically does not have the proper level of scrutiny, and/or the user interface is not intuitive, thereby increasing the risk for operator error. A number of installations have had related issues and have added to the plant owners' perceived risk. In contrast, GE has been able to apply Six Sigma® and new product introduction tollgate process rigor to reduce digital upgrade risk. With nuclear turbine control digital upgrades, for example, a rigorous software design and code verification, a single point failure analysis, a failure modes and effects analysis (FMEA), and a reliability study were performed along with extensive verification, validation, and factory acceptance testing. GE performs these types of processes and procedures as well as human factors engineering (HFE) on nuclear digital controls for both safety and non-safety implementations, reducing the risks and allowing smooth implementations.

### Nuclear Steam Supply Systems (NSSS)

The NSSS are valuable plant assets that require extensive management to ensure successful operation and acceptable lifetimes. For BWRs, GE is working with customers to develop a health monitoring system that will provide risk-based prioritization for asset management of NSSS components. The health monitor will combine information on material performance (e.g., crack growth monitoring), environmental factors (e.g., electrochemical corrosion potential in the primary coolant and water chemistry monitoring), and periodic plant and equipment inspections (e.g., in-vessel visual inspections and pool-side fuel assembly inspections) to define a proactive maintenance and asset replacement strategy aimed at extending plant lifetimes. [4]

### Reactor Recirculation Pump Shaft Crack Case History

This issue of ORBIT includes a review of a reactor recirculation pump shaft crack investigation by Ronald Bosmans (page 38). It pertains directly to NRC Information Notice 2005-08 Alert regarding "the importance of timely detection of circumferential cracking of reactor coolant pump (RCP) and reactor recirculation pump (RRP) shafts to minimize the likelihood of consequential shaft failures." The vibration monitoring recommendations are important to BWRs, but may well be more important to PWRs as an RCP seal failure can be more safety-significant by increasing the likelihood for a Loss of Coolant Accident (LOCA).

### Bently Nevada™ Asset Condition Monitoring—Radiation Resistant Sensors

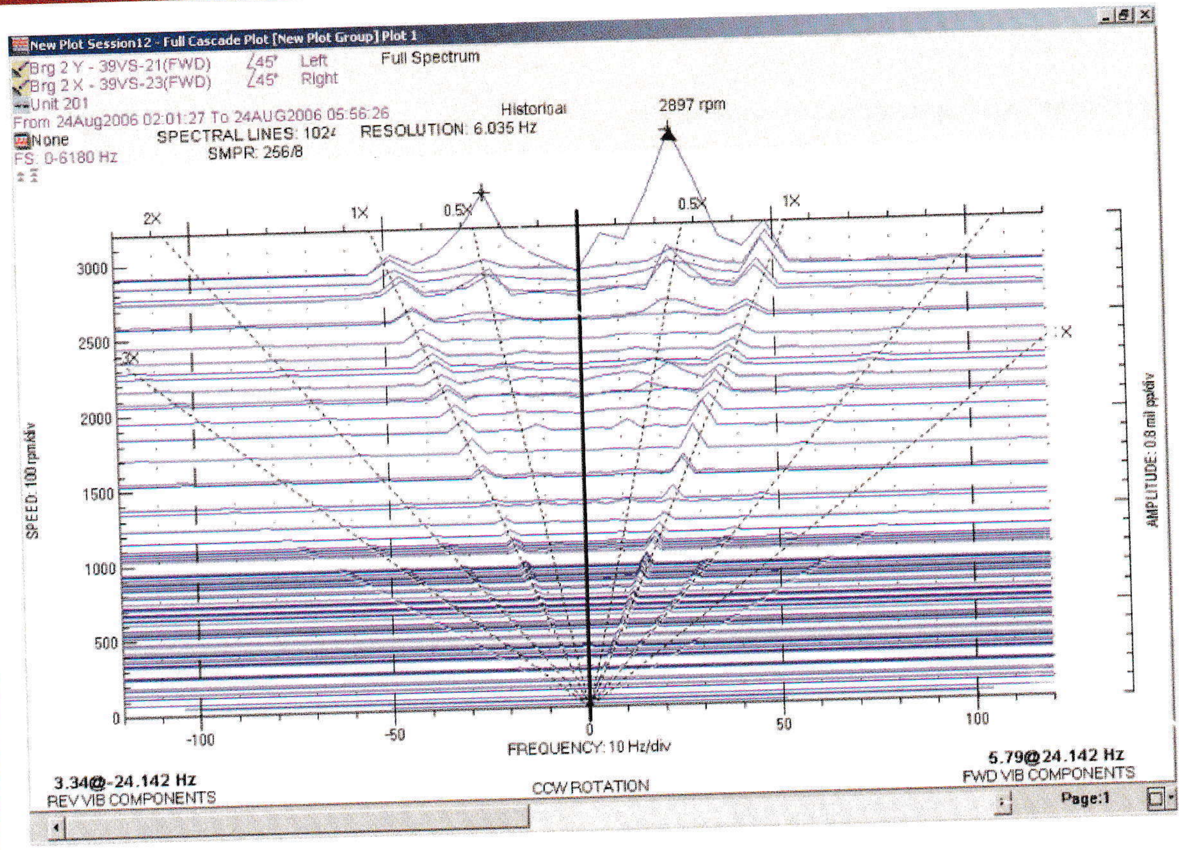
GE recently introduced two new Bently Nevada™ Asset Condition Monitoring products for vibration monitoring in a nuclear environment—the Radiation Resistant 3300 XL Proximitor® and 330530 Velomitor® sensor (page 21). The radiation-resistant designs ensure signal integrity in nuclear radiation environments, longer service life due to lack of moving parts, and ease of installation. The radiation-resistant designs and testing incorporate our Reuter Stokes expertise, as well, to ensure signal integrity in nuclear radiation environments, longer service life due to lack of moving parts, and ease of installation.

### Integrated Turbine Supervisory Instrumentation & Control Solution

Integrated controls are essential in today's world. On the main steam turbine unit, GE provides a unique combination of monitoring, control, and protection through an integrated Turbine Supervisory Instrumentation (TSI) system for the main steam turbine unit, feed pump turbine and auxiliaries. The TSI system combines the highly reliable control of the Mark VI platform controller with the industry-standard Bently Nevada™ 3500 series monitoring and protection system. Through unit and plant data highways, the information from these systems is integrated with GE's System 1® optimization and diagnostics software platform. Using Decision Support℠ capabilities within System 1, anomalies can be detected and evaluated to determine if there is an issue with the process or with the machinery. From there, Actionable Information® advisories can automatically be sent to the appropriate resource(s) for corrective action.

A recent example will help illustrate the importance of this integration. A customer was coming out of an outage and only had vibration setpoints enabled for 1X frequency vibration in the machine control system. During startup, 3500/System 1 detected a 0.475X frequency vibration, and, fortunately, the customer observed the vibration indication and manually shut down the turbine. 3500/System 1 captured the entire startup, and after reviewing the available data (Figures 6 & 7), a machinery diagnostics engineer was able to determine that it was a fluid induced instability. With this information, the customer was able to then narrow troubleshooting to an improperly installed valve. In this case, the machine protection was done via the control system only, limiting the functionality. With a fully integrated system, protection is distributed between 3500 and the machine control system, providing more flexibility for automation of machine protection as well as proactive diagnostic capability.

With a fully integrated solution (Figure 8), proactive notification and alarming would have been provided to engineering and monitoring experts via System 1's Smart Notifier. Operator notification is provided by the controller-human-machine interface. When the alarms reached a point that the machine needed to be protected, the turbine would be automatically shut down or pre-alarms could have provided notification to experts prior to the shutdown conditions. The problem could have been analyzed and then resolved quickly utilizing System 1 Decision Support functionality.


New Plot Session12 - Full Cascade Plot [New Plot Group] Plot 1

Brg 2 Y - 39VS-21(FWD) ∠45° Left

Brg 2 X - 39VS-23(FWD) ∠45° Right

Full Spectrum

Unit 201

From 24Aug2006 02:01:27 To 24AUG2006 05:56:26

Historical

None

SPECTRAL LINES: 1024 RESOLUTION: 6.035 Hz

SMPR: 256/8

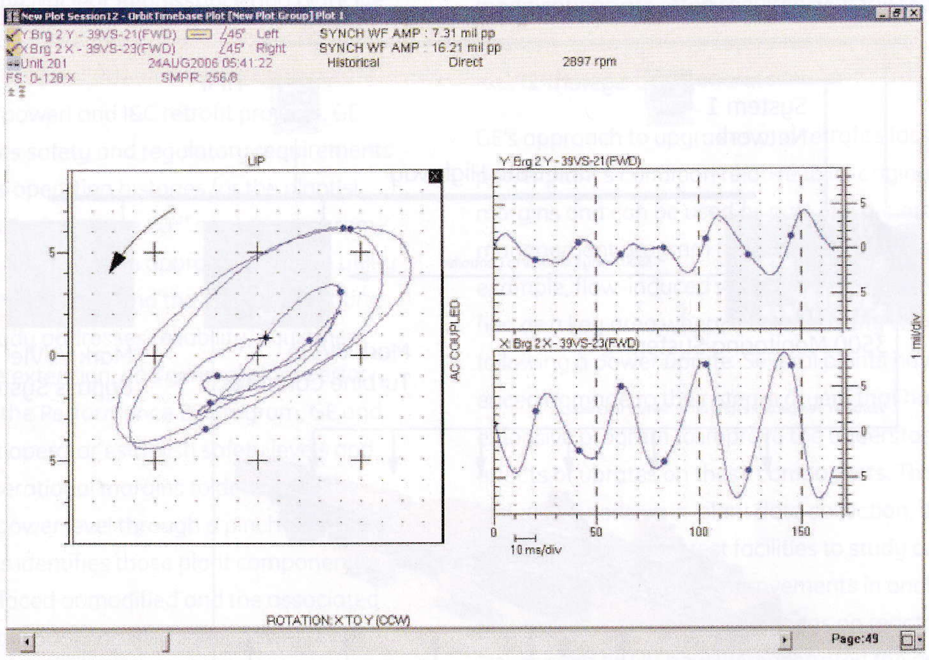
FS: 0-6180 Hz

3.34@-24.142 Hz
REV VIB COMPONENTS

5.79@24.142 Hz
FWD VIB COMPONENTS

Figure 6 – Cascade plot of fluid induced instability.

Figure 7 – Orbit/timebase plot of fluid induced instability.



ANNOUNCEMENT

GE
Energy

Advancing the Nuclear Renaissance:
2007 Nuclear Instrumentation and Control Users' Conferences

Move ahead on the path to plant profitability and reliability:

**Madrid, Spain – March 26-30**

**Wilmington, North Carolina, USA – June 19-20**

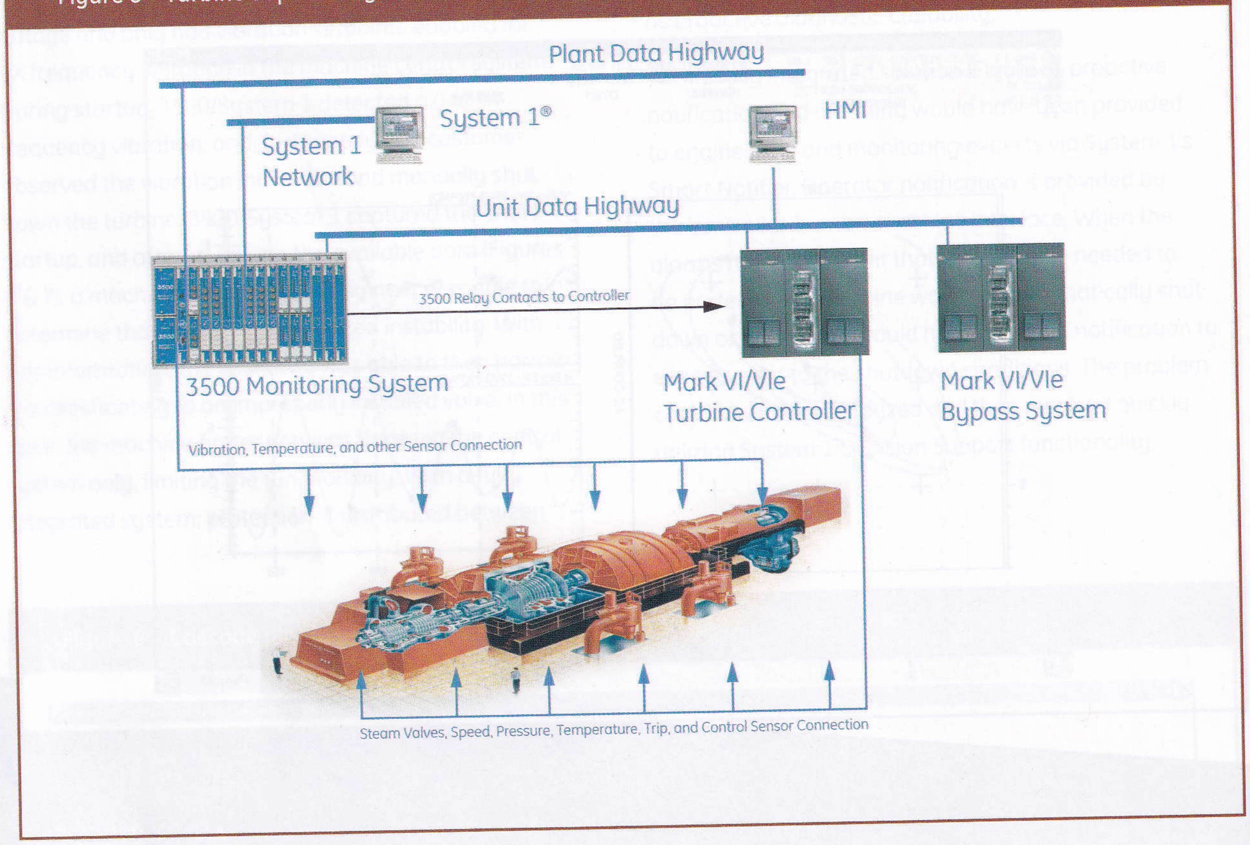
Each conference will bring together diverse users of hardware, software and services that span Reuter Stokes™ nuclear instrumentation, neutron monitoring, nuclear plant control, and Bently Nevada™ Asset Condition Monitoring. You'll learn:

- Why and how integrating instrumentation, control, and condition monitoring systems creates a powerful I&C solution
- How to get more from your systems through comprehensive educational sessions
- How others are applying their systems in new and innovative ways
- The future of instrumentation and control technologies

For more information, contact Betsy Mauchley at betsy.mauchley@ge.com

imagination at work

Figure 8 – Turbine Supervisory Instrumentation (TSI) integrated solution.


Plant Data Highway
System 1®
HMI
System 1 Network
Unit Data Highway
3500 Relay Contacts to Controller
3500 Monitoring System
Mark VI/VIe Turbine Controller
Mark VI/VIe Bypass System
Vibration, Temperature, and other Sensor Connection
Steam Valves, Speed, Pressure, Temperature, Trip, and Control Sensor Connection

> “In a base-load nuclear power plant, keeping the plant running is of paramount importance. Downtime in one of these large plants can cost 0.5 to 1 million USD in lost

## Plant Performance Improvements

In response to the Nuclear Renaissance and plant life extensions (PLEX), reliability is the key to success. In Extended Power Uprate (EPU—defined as up to a 20% increase in plant power) and I&C retrofit projects, GE not only integrates safety and regulatory requirements but also assesses operating histories for the plant(s) involved. With its Performance 20$^{SM}$ analysis program, GE implements a collaborative approach with the utility focusing on both the design and the current operating condition. The study addresses reliability, equipment obsolescence, life extension, and general plant performance. Through the Performance 20 program, GE and the nuclear plant operator establish safety levels and then evaluate operational margins to determine the optimum target power level through a pinch-point analysis. This analysis identifies those plant components that must be replaced or modified and the associated economics to allow pursuing the higher power levels and the life extension goals. When combined with the EPU pinch-point analysis, the Performance 20$^{SM}$ study helps avoid the redundant modification risk by ensuring that changes are implemented in a staged and efficient manner, avoiding additional changes in later years due to the implementation of an EPU. In an EPU, major modifications are often required with the reactor recirculation system, the reactor pressure vessel internals, I&C, and the turbine generator.

GE's approach to upgrades and retrofits factors in the power plant's condition relative to its original design margins and can be used as part of a general life cycle management program for reliability purposes. For example, flow-induced vibration (FIV) has been identified as a key area where increased duty is expected following a power uprate. Several plants have experienced damage to their steam dryers that has lead to an extensive program to improve the understanding of the effects of uprates on these components. This program includes extensive in-plant data collection, the development of scale model test facilities to study components susceptible to FIV, and improvements in analytical techniques for evaluating loadings on reactor internals. Issues such as FIV have demonstrated the need for a comprehensive review of plant conditions prior to implementation of a power uprate and advanced testing and analytical techniques to address the consequences of changes in operating conditions.

> revenue per day, or more...Asset condition monitoring is a key enabler of maintenance and reliability program success. ”

## Summary

The nuclear industry has reached a level of maturity where the lessons learned in the past 50 years are being applied: passive safety power plant designs; proven technology; modular build process; and improved regulatory processes. Existing power plants are going through life extensions and power uprates while capacity factors continue to improve. The need for improved maintenance and reliability is driving new I&C installations. GE provides a broad range of I&C solutions tailored to the nuclear industry (Figure 9).

GE has been in the nuclear industry from the beginning and has been a key contributor to the maturity of the industry. We are leveraging this 50+ years of proven experience along with investments in new technology to ensure that industry needs are met for both the existing retrofit market and the next-generation of new nuclear power. Our experience, combined with leading large rotating equipment capability (e.g., energy, industrial, oil & gas, and aircraft engines) and I&C expertise (e.g., Bently Nevada™ Asset Condition Monitoring, System 1® optimization and diagnostics software, Reuter Stokes Measurement Solutions, nuclear safety and power plant controls, and services—both transactional and contractual), demonstrate a leading set of robust solutions for multiple plant systems throughout the plant, while effectively managing the regulatory approval cycle. Nuclear Renaissance aside, these solutions are available to solve today's problems and move the industry forward for the next 50 years.

[1] Nuclear Energy Institute (NEI): compiled from U.S. Bureau of Labor Statistics - 2004 Industry Safety Accident Rate

[2] NEI and World Association of Nuclear Operators (WANO)

[3] U.S. Nuclear Regulatory Commission public hearing transcript on Digital Upgrades 8 November 2006

[4] Spanish Nuclear Society 2006 - Asset Management by Glen Watford, GE Energy

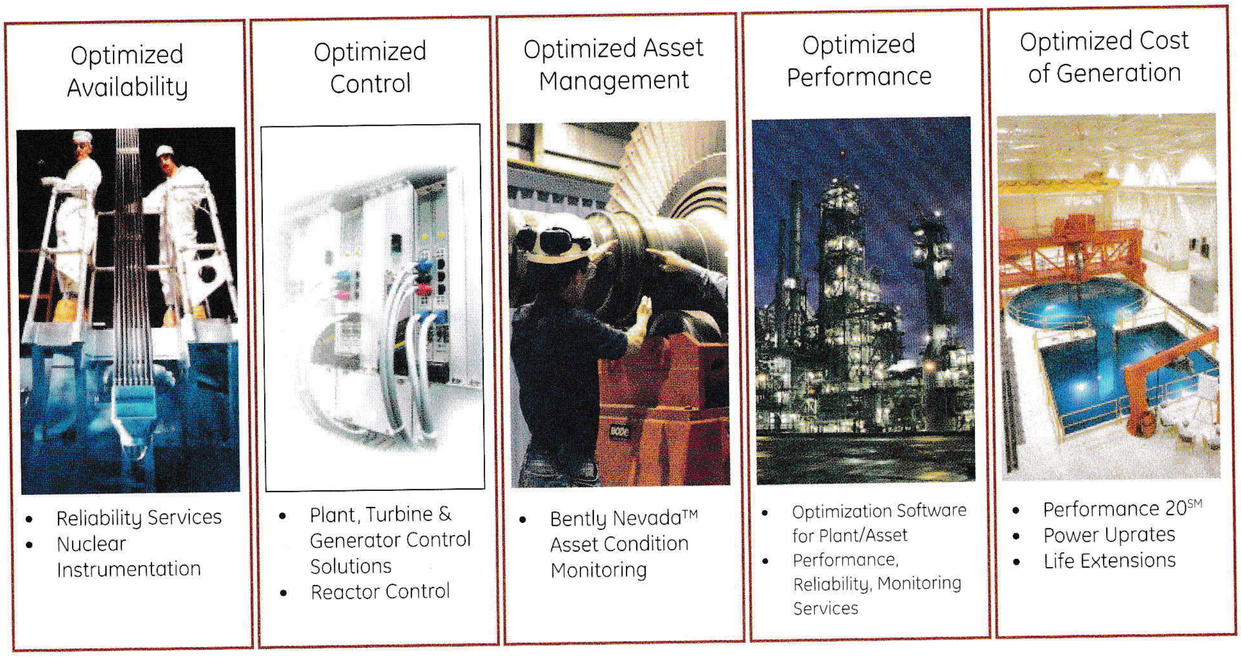

Optimized Availability
• Reliability Services
• Nuclear Instrumentation
Optimized Control
• Plant, Turbine & Generator Control Solutions
• Reactor Control
Optimized Asset Management
• Bently Nevada™ Asset Condition Monitoring
Optimized Performance
• Optimization Software for Plant/Asset Performance,
• Reliability, Monitoring Services
Optimized Cost of Generation
• Performance 20℠
• Power Uprates
• Life Extensions

**Figure 9 – GE Energy's nuclear instrumentation and control solutions.**

# Questions & Answers

## *A conversation with Andy White, President and CEO of GE Energy's nuclear business*

**O: What are the prospects for new nuclear power plants in the U.S.?**

AW: The outlook is very good right now. The industry needs to move forward in the current window of opportunity. Simplified modular power plant designs such as ESBWR with a 36-month build cycle, improved regulatory procedures, build incentives, and solid economics make nuclear a prime candidate for base-load additions. Existing plants' safety records and continued performance improvements further add to the Nuclear Renaissance. The fact that the generation of nuclear power eliminates millions of tons of emissions annually is also very favorable.

**O: Which countries around the world do you believe will be opening up to new nuclear build?**

AW: It truly depends, country to country—government's favorability toward nuclear means a great deal. Globally, the chances are very good. Pinpointing which countries and which vendors' plants will go forward first and its timing is very difficult. But, we can expect some to go forward. For GE, countries such as Taiwan, Finland and Japan will continue their new build initiatives and we feel positive about being involved. We also see countries like India, UK and Canada as very promising new build opportunities. At some point in the next year or so, we additionally believe we will receive new interests from countries like Turkey, who are just beginning to seriously look at building nuclear.

**O: GE Energy's Bently Nevada and Reuter Stokes product lines have a long legacy in the nuclear industry. How do these I&C products fit into the Nuclear Renaissance?**

AW: Both of these product lines have a rich 50-year history. When our customers purchase these products, they are also getting a service—tremendous experience and engineering support. Our customers need improved reliability, operations, and safety—Bently Nevada and Reuter Stokes solutions assist in meeting these goals. Many of our customers are formalizing this relationship with long-term contractual agreements to fully benefit from our knowledge and skills.

**O: How does GE address the key obstacles to digital upgrades?**

AW: Digital upgrades improve capacity factors, reduce forced outages and address analog obsolescence issues. The risks and costs of obsolescence are high and often underestimated. We want to avoid a situation where there is an extended outage at a plant due to an obsolescence issue that could be avoided with a digital upgrade. GE has implemented several digital nuclear upgrades, and our experience with digital technologies on new builds (3rd Generation Advanced Boiling Water Reactor) puts us in a good position to lead digital upgrades.

**O: There have been recent consolidations between nuclear suppliers (one example: Toshiba-Westinghouse). Do you see this trend continuing?**

AW: Merger and acquisition activity in the industry will likely continue both on the supplier and utility side, but it is probably not going to be of the scale or at the price premium of Toshiba-Westinghouse. Consolidations will most likely focus on areas where sharing resources and technology will provide specific product and service synergies for customers. GE most recently signed a letter of intent with Hitachi to negotiate the formation of a global alliance that will combine our new nuclear power plant and services businesses. This will strengthen our existing operations, expand our global footprint, give us greater scale to accelerate the development of new products and services, and position us for growth in the nuclear energy segment.

We are currently completing our due diligence process for the deal and expect to conclude this over the coming weeks, with a planned first half 2007 transaction completion.

**O: On December 9, 2006 the U.S. Congress passed the U.S.-India Peaceful Atomic Energy Cooperation Act. What impact and opportunity does this passage represent for GE?**

AW: Foremost, it will end India's nuclear isolation of more than three decades and allows the U.S. to participate in civilian nuclear trade with India. GE was the provider of the first reactors ever placed in India—Tarapur 1 and 2. While they are India's oldest reactors, they are reportedly the best operating reactors in India.

*(continued on next page)*

## *A conversation with Andy White...continued*

Providing that government negotiations yield positive results, a huge opportunity will open up for GE's nuclear business—in terms of new units, services, and fuel.

We are excited about nuclear opportunities in India. I became the first President and CEO of GE Energy's nuclear business to visit India since the international embargo on nuclear technology exports to India in 1974. During my visit I met with government officials and prospective customers and suppliers. This very successful visit allowed GE the opportunity to state our commitment to participate in India's civilian nuclear energy program—should the political and legal issues be resolved, thereby enabling a regulatory framework to be created.

India presently has a target of generating 20,000 megawatts of nuclear power by 2020. Such a large-scale increase in nuclear power generation will require partnerships, and GE has great relationships with Indian industrial firms. In fact, one of our global technology centers—the John F. Welch Technology Center—is located in Bangalore.

**O: What key improvements has the nuclear industry experienced over the last 10 years and how will this affect the future Nuclear Renaissance?**

AW: The industry has followed a model of both government and self-regulation with continuous improvement. It has embraced technological advances ranging from more efficient fuel assemblies to next-generation reactor designs that will be even safer and more fuel-efficient. For instance, our ESBWR technology design has improved economics, security, and lower O&M costs. It is game-changing technology that is largely based on our proven, operating Advanced Boiling Water Reactor. For new plants, combining the past 50 years of nuclear experience to develop advanced technologies has broken the historic paradigm that new build is expensive and time consuming. These improvements are even being applied to the retrofit market to further enhance performance and power output and to extend plant life.

This operational success combined with the compelling economic, political, and environmental advantages of nuclear power will have a direct impact on how quickly the Nuclear Renaissance is implemented.

FROM THE DESK OF

# More Technology... Closer to Our Customers

The leadership of Optimization and Control hope that each of you experienced a successful 2006—personally, with your teams, and for your entire organizations. Regardless of how we work together, we commit to support you and help you deliver even greater successes in 2007. Let me share our perspective on "Marketing" and discuss some of our many ongoing efforts.

To us, Marketing is the bringing together of all our global organizational capabilities to compete effectively today, so we can deliver to you leading technologies and skills and help you deliver unique value to your customers. As we look to increase our performance for you, I'll share some progress in technology and product development, global local investment, and expansion of some traditional marketing communication efforts—all aimed to both increase our technology capabilities and to enable us to better deliver these capabilities and training to all our customers in their local regions.

John Cataldo
General Manager, Marketing and Commercial Operations
Optimization and Control
GE Energy
john.cataldo@ge.com

Concerning technology and product development, we continue to invest tens of millions of dollars annually to develop innovative products and services. In general, we are developing more scalable and broadly expanded asset solutions for condition monitoring and controls, and an expanded scope in our Reuter Stokes nuclear instrumentation. In condition monitoring, for example, we have moved beyond vibration measurement and analytics to others like hydro air gap, reciprocating compressor cylinder pressure, and generator partial discharge. New software tools include neural net analytic technology to solve previously "impossible" challenges. In Control Solutions, we have fielded an entirely new approach for our customers to upgrade from 1980s Mark IV technology to state-of-the-art Mark V controls by simply "plugging in" new internals while leaving the panels and connections intact. In Services, we are pioneering a new approach combining condition monitoring expertise with deep plant reliability understanding to allow you to dramatically improve your plant-level reliability and availability.

> "Customer Application Centers are one of many regionally focused initiatives, all intended to bring our business closer to you and to drive your voice into our business resource and new product development planning."

Regarding global local investment, our Region Leaders are bringing much more local decision-making authority and technical resources into your regions. Our new Customer Application Centers (CACs), which many of you have already experienced, are a great example. These CACs provide more in-depth personal training, broad product application demonstrations, factory acceptance testing, and direct face-to-face work with engineering talent in modern new local facilities. CACs are now operating in Singapore, Moscow, Florence, and Houston. Others opening in 2007 will be Campinas, Mumbai, Shanghai, and Jebel Ali. Customer Application Centers are just one of many regionally focused initiatives, all intended to bring our business closer to you and to drive your voice into our business resource and new product development planning.

With our marketing communications, in 2007 we will expand our sponsorship of Customer User Conferences to all regions—Americas, Europe, Africa/India/Middle East, and Asia. Those of you returning from our 2006 conferences will find more time dedicated to your presentations and to face-to-face, hands-on work with our experts on techniques to better utilize the variety of condition monitoring and controls tools. As another example, we recently launched a new website at www.ge-energy.com/oc that provides more extensive information on our technologies and applications yet offers an improved design where things are much easier to find. Additional sites are planned for 2007 and will include local language content, expanded solution examples, and more.

We commit to relentlessly pushing ourselves and Optimization and Control to help you win now and in the future. We will continue our drive to be ever more vigorous competitors and to deliver you more value.

# Shaft Crack

## Detection Methodology for Reactor Coolant & Recirculation Pumps

During the normal operation of Reactor Recirculation Pumps (RRPs) and Reactor Coolant Pumps (RCPs), the rotors are subjected to stresses. Depending upon the magnitude of the summation of forces and the accompanying induced stresses, the fatigue limit of the material may be exceeded. Failures may occur due to high- or low-cycle fatigue. Material failures will result in the initiation of a shaft crack, with a crack potentially propagating sufficiently to cause total failure of the rotor. This article discusses the vibration symptoms that indicate the presence of a cracked rotor and the required monitoring system for early detection. It includes a brief case history with field-acquired vibration data from an RRP operating under shaft crack conditions, where the unit was successfully removed from service prior to a total shaft failure.

### Typical Sources of Operating Forces

- Unbalance forces
- Hydraulic forces—radial sideloads
- Torsional forces
- Longitudinal bending
- Misalignment
- Temperature gradients*

*Significant alternating thermal gradients occur in RRPs where the cooled stuffing box fluid mixes with the hot Reactor Coolant System (RCS) fluid.

One of the key contributing forces acting on the impeller and rotor is the hydraulic side load force or radial thrust force. The magnitude and direction of this force is dependent upon the design of the volute casing and the current flow rate versus the design flow. Radial thrust force is described as follows:

$$F = (K * H * D_2 * B_2) / 2.31$$

**$F$** is the radial thrust force, in pounds

**$H$** is the pump head, in feet

**$D_2$** is the impeller diameter, in inches

**$B_2$** is the impeller overall width, in inches

**$K$** is a constant, which varies with pump specific speed and flow rate

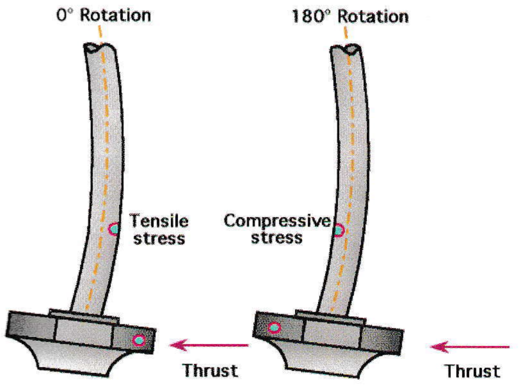
**$K$** varies from 0.01 to 0.12 at Best Efficiency Point (BEP)

When the pump is operated significantly above or below the design flow (BEP), as occurs at startup in BWR plants, the radial thrust force can become a large side load force, $K \rightarrow 0.4$. This typically causes fully alternating bending stress in the rotor as shown in Figure 1.

The radial thrust force, in combination with impeller vane interaction forces, may introduce sufficient stress levels to facilitate propagation of thermally initiated cracks and lead to fatigue failure of the rotor.

Ronald Bosmans
Global Machinery Diagnostics Services Manager
Optimization and Control Services
GE Energy

**Figure 1 – Radial sideload causes cyclical bending stress in pump shaft.**



## Stress Equations

The governing stress equations for mechanical loads, resulting from operating forces, are as follows:

### Nominal stress equations (solid shaft)

**Bending stress**

$\sigma_b = (4 * M) / (\pi * r^3)$

**Axial Stress**

$\sigma_a = F / (\pi * r^2)$

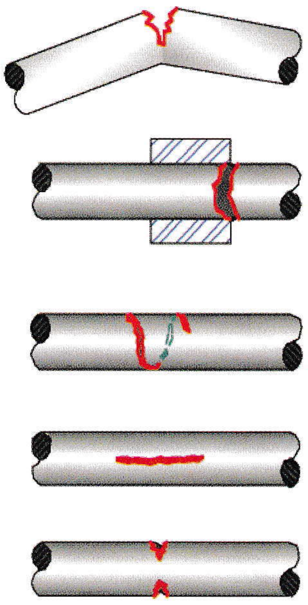
**Torsional stress**

$\tau = (2 * T) / (\pi * r^3)$

**Combined stress intensity**

$\sigma = [(\sigma_a + \sigma_b)^2 + 4 * \tau^2]^{0.5}$ * Stress Concentration Factors

**Figure 2 – Types of cracks leading to shaft failure and their frequency.**



| | |
|---|---|
| Transverse | Frequent |
| Tensile | Less Frequent |
| Torsional | Less Frequent–<br>*except in final stage of transverse break* |
| Longitudinal - Thermally Induced | Rare–*usually arrested unless mechanical loads turn longitundinal cracks circumferentially* |
| Symmetric | Rare |

## Shaft Crack Symptoms

Shaft cracks introduce a reduction in the cross-sectional area of the rotor and a subsequent reduction in the stiffness of the rotor. This also causes an asymmetry of the stiffness properties of the rotor in the radial direction. The rotor's deflection (bending), in response to operational forces (unbalance, hydraulic, misalignment, etc.), will begin to increase as the crack continues to propagate. This will increase the synchronous (1X) vibration component. In addition, the stiffness asymmetry will also manifest in an increase in the 2X vibration component. The propagation of a crack around the shaft circumference and radially inward is a very non-linear mechanism. Therefore, vibration changes may be gradual over time, but also may indicate erratic changes over time.

## Shaft Crack Indicators

### 1X vibration behavior

- An increase in the synchronous (1X) vibration levels
- 1X increases may be gradual over time, but are often step changes as the crack grows
- Continuous 1X phase changes that may be gradual over time, but also may be very erratic with step changes

*Note 1: 1X vector data must be compensated for measurement run out errors.*

### 2X vibration behavior

- An increase in the 2X vibration over time
- 2X vibration is caused by the asymmetry of the rotor as the crack propagates.
- Radial side load or radial thrust increases the amount of observed 2X vibration.
- Based upon acquired field data and experimental lab studies, the 2X vibration is typically detectable after the crack has penetrated to 20–30% of the cross-sectional area of the rotor. 2X phase changes will occur over time. They may be gradual or step changes.

*Note 2: 2X may indicate rapid changes of amplitude and phase if the pump speed is ½ the frequency of any resonance.*

## Vibration Plots for Shaft Crack Detection

### Steady state data

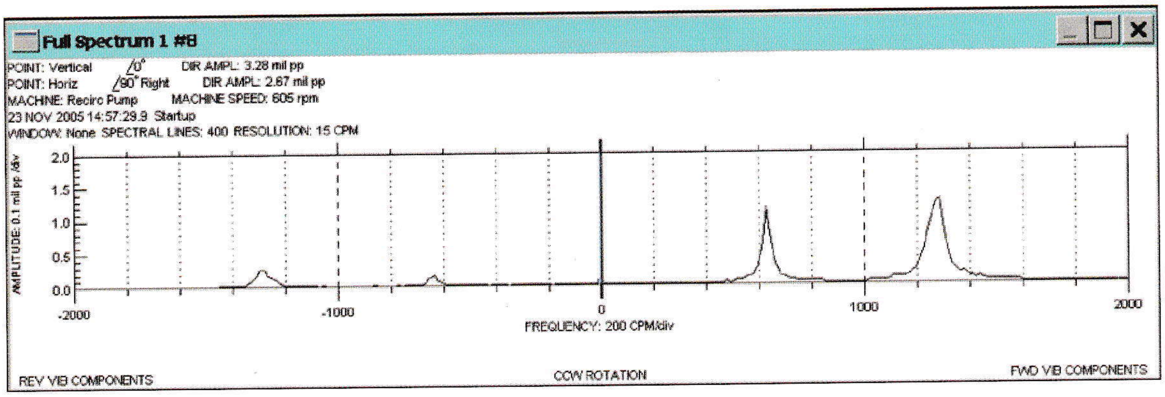
- Trend plots of 1X and 2X amplitude and phase angle
- Full Spectrum plots – Waterfall
- Orbits and Timebase plots
- Polar plots versus time with Acceptance Region alarming

### Transient data – startup or shutdown

- Bode and Polar plots
- Orbits and Timebase plots – 1X, 2X, Direct
- Full Spectrum – Cascade plots

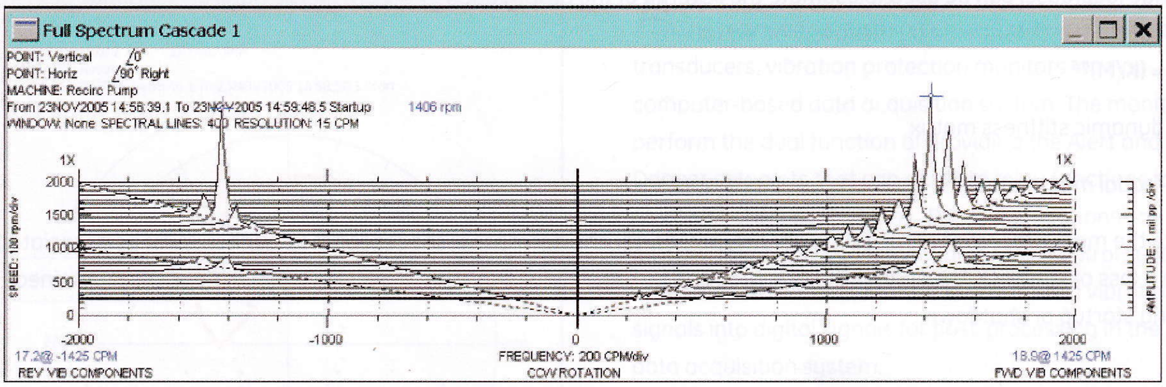
## Typical Vibration Plots

**Figure 3 – Full Spectrum plot.**



POINT: Vertical /0° DIR AMPL: 3.28 mil pp
POINT: Horiz /90° Right DIR AMPL: 2.67 mil pp
MACHINE: Recirc Pump MACHINE SPEED: 605 rpm
23 NOV 2005 14:57:29.9 Startup
WINDOW: None SPECTRAL LINES: 400 RESOLUTION: 15 CPM

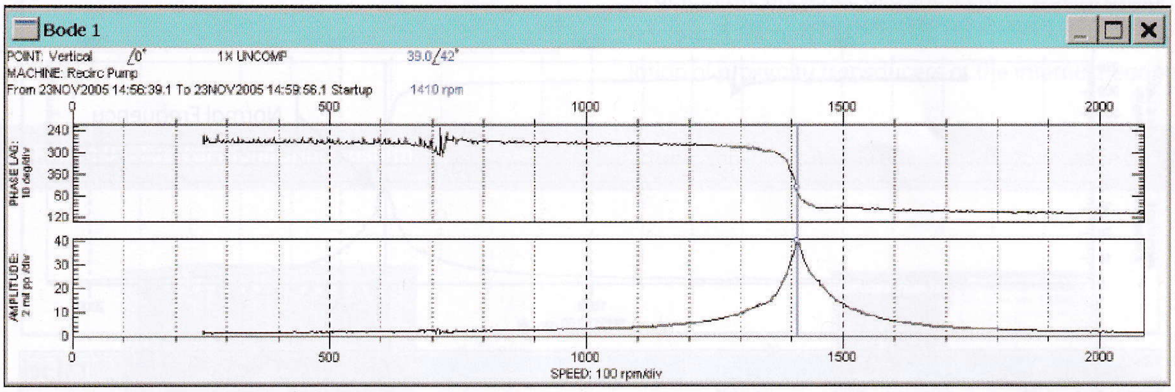
Figure 4 – Full Spectrum Cascade plot.



Full Spectrum Cascade 1

POINT: Vertical ∠0°
POINT: Horiz ∠90° Right
MACHINE: Recirc Pump
From 23NOV2005 14:56:39.1 To 23NOV2005 14:59:48.5 Startup 1406 rpm
WINDOW: None SPECTRAL LINES: 400 RESOLUTION: 15 CPM

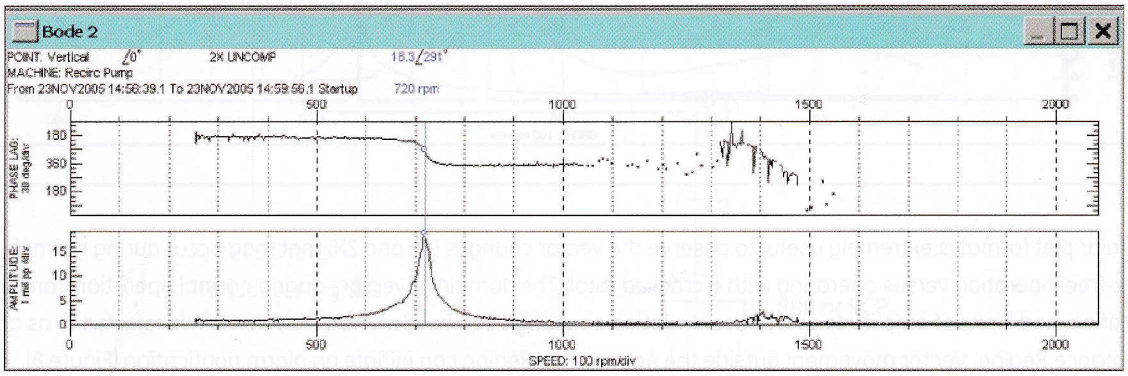
Figure 5 – Bode plot of the 1X vibration.



Bode 1

POINT: Vertical ∠0° 1X UNCOMP 39.0∠42°
MACHINE: Recirc Pump
From 23NOV2005 14:56:39.1 To 23NOV2005 14:59:56.1 Startup 1410 rpm

Figure 6 – Bode plot of the 2X vibration.



Bode 2

POINT: Vertical ∠0° 2X UNCOMP 18.3∠291°
MACHINE: Recirc Pump
From 23NOV2005 14:56:39.1 To 23NOV2005 14:59:56.1 Startup 720 rpm

The transient data is one of the key indicators of the presence of a crack and its severity. As the pump shaft weakens due to a propagating crack, the frequency of the balance resonance (critical speed) also decreases. The amount of change (decrease) can be used to estimate the severity of the propagation of the crack. The natural resonance of a rotor system is determined by the following equation:

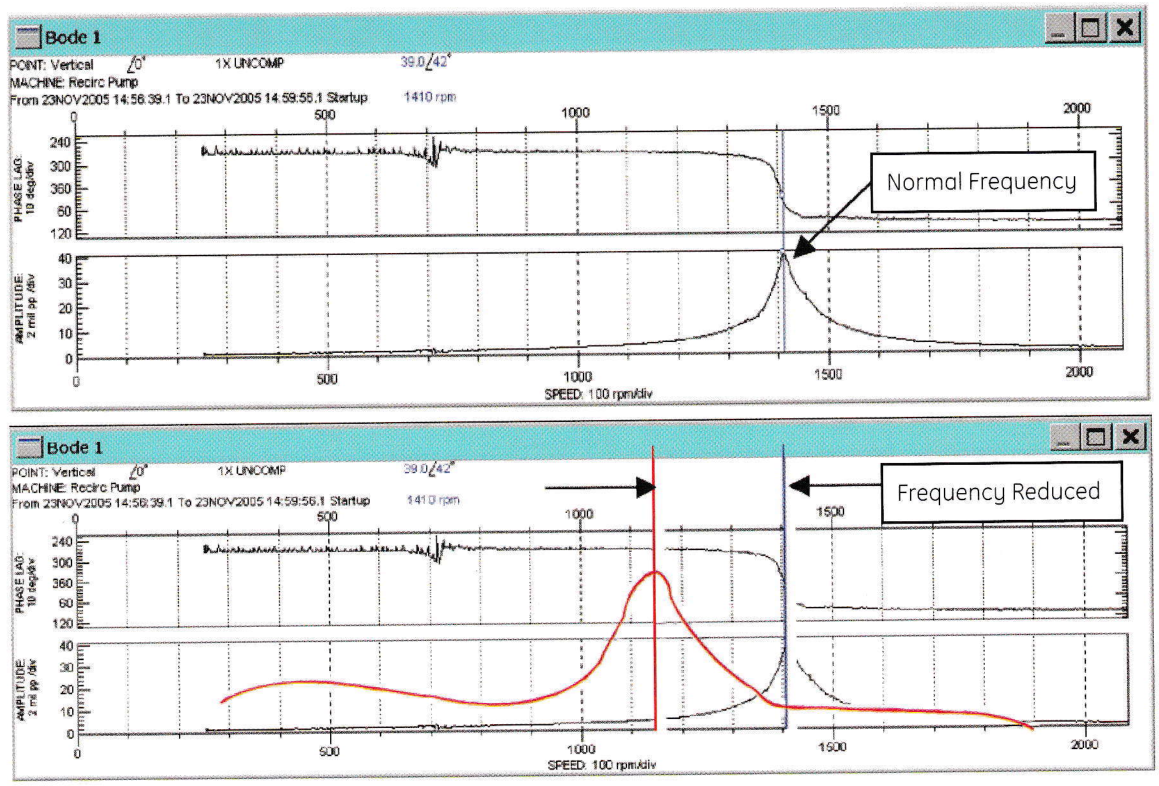
$$\omega_{res}= (K/M)^{0.5}$$

**K** = dynamic stiffness matrix

**M** = modal mass matrix

Since the mass properties of the pump are not increasing, any decrease in the resonant frequency must be associated with a loss of stiffness. The change in frequency can be determined from the Bode (Figure 7) and Polar plots obtained during startup or shutdown.

**Figure 7 – Bode plot – reduced resonance frequency.**



Bode 1

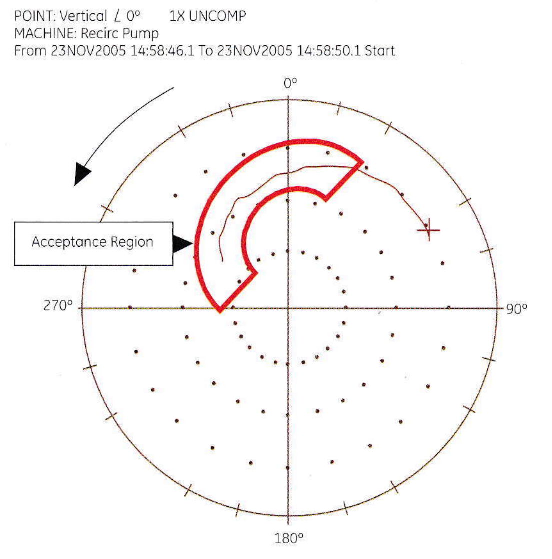
POINT: Vertical ∠0° 1X UNCOMP 39.0∠42°

MACHINE: Recirc Pump

From 23NOV2005 14:56:39.1 To 23NOV2005 14:59:56.1 Startup 1410 rpm

The Polar plot format is extremely useful to observe the vector changes (1X and 2X) that may occur during normal (crack-free) operation versus operating with a cracked rotor. The domain of vectors during normal operation can be quantified, and limits of amplitude and phase deviation or change can be identified. This domain is referred to as an Acceptance Region. Vector movement outside the Acceptance Region can initiate an alarm notification (Figure 8).

Figure 8 – Acceptance Region Polar plot showing rapid changes during shaft crack event.



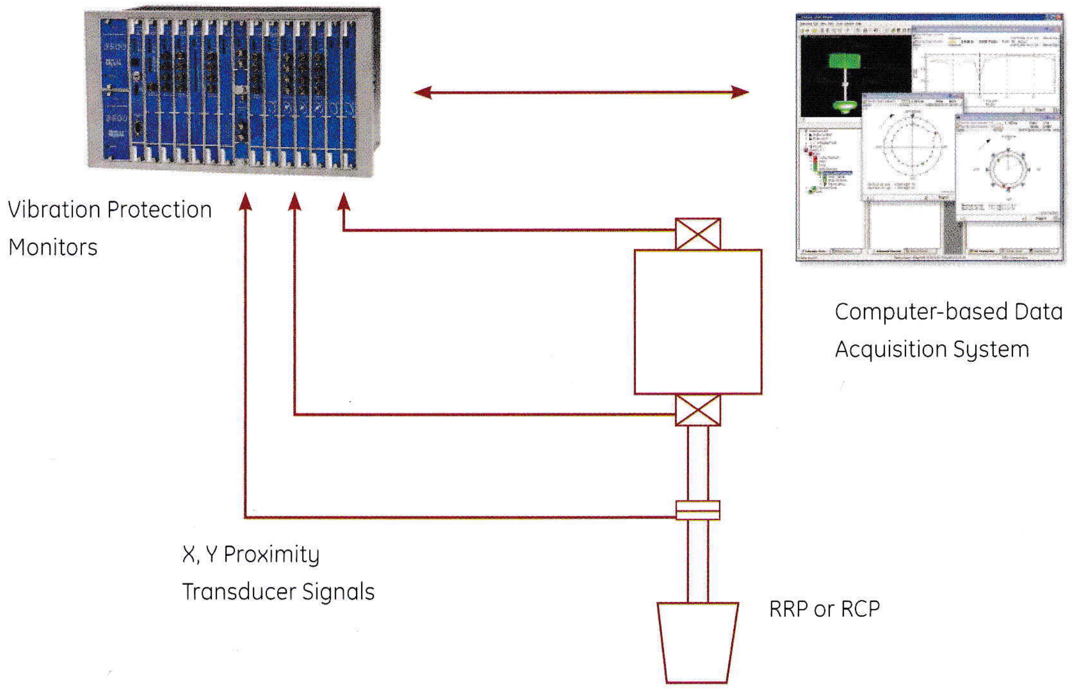
## Monitoring Systems

A typical monitoring system is shown in Figure 9. The monitoring system consists of measurement transducers, vibration protection monitors, and a computer-based data acquisition system. The monitors perform the dual function of providing the Alert and Danger setpoints that can activate relay functions to alert operators to problems. The relay functions can also be integrated into a shutdown logic control system. In addition, the monitors convert the analog vibration signals into digital signals for post-processing in the data acquisition system.

### Transducers

Proximity transducers observing the pump and motor rotors must be utilized to provide the necessary data to detect the presence of a shaft crack. Due to design and the RCPs' and RRPs' radiation environment, installation of proximity transducers at the internal bearing

Figure 9 – Typical monitoring system.



area of the pump is not possible. Two transducers are required, mounted orthogonal (XY) at each plane of measurement. The measurement plane for the pump rotor should observe the lower coupling hub or the exposed pump shaft. Proximity probes should also be located at the upper and lower motor radial bearings. Two proximity transducers observing the thrust collar should also be utilized for axial position and dynamic vibrations in both the pump and the motor. Seismic (velocity) transducers mounted on the upper and lower motor bearing housings can also be used for additional data. A Keyphasor® transducer must also be installed at the coupling area to provide speed and phase data.

### Vibration Protection Monitors

The monitors should be rack-mounted and provide continuous (24/7) monitoring and protection of the motor and pump. They can be simple radial vibration monitors or monitors that also include programmable setpoint and alarming criteria (e.g., monitors able to provide hardware alarms if the 1X or 2X vectors [amplitude or phase] violate Acceptance Regions for normal operation). Since cracked shaft behavior invariably produces changes in the 1X and 2X behavior, monitors that can recognize aberrant behavior and provide alarming are highly desirable.

### Computer-based Data Acquisition System

In order to observe changes of the pump behavior over time, a computer-based data acquisition system is necessary. The system can present plots indicating trend value changes, Orbit changes, vibration frequency changes, and 1X and 2X vector changes. The system must be capable of capturing the dynamic data during startups and shutdowns. This data capture supports the use of Bode and Polar plots as well as Full Spectrum Cascade plots.

> “...transient data is one of the key indicators of the presense of a crack and its severity.”

Figure 10 – Trend files.

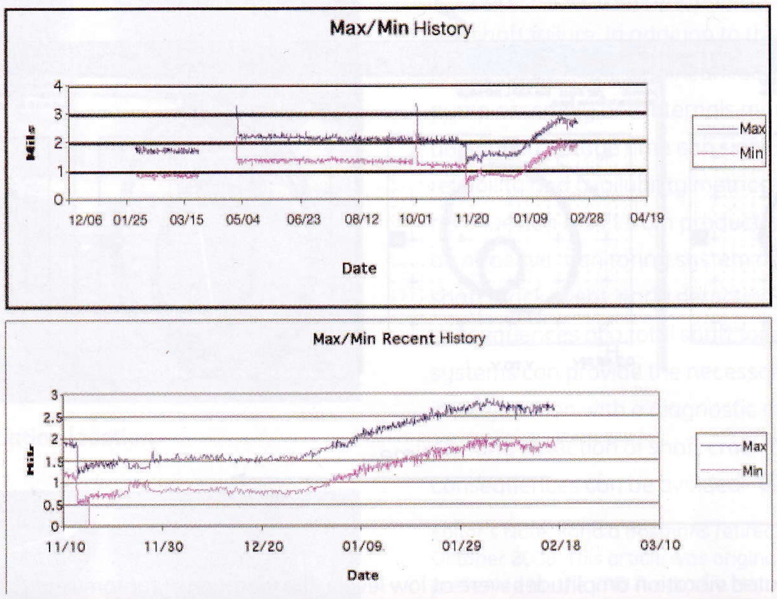
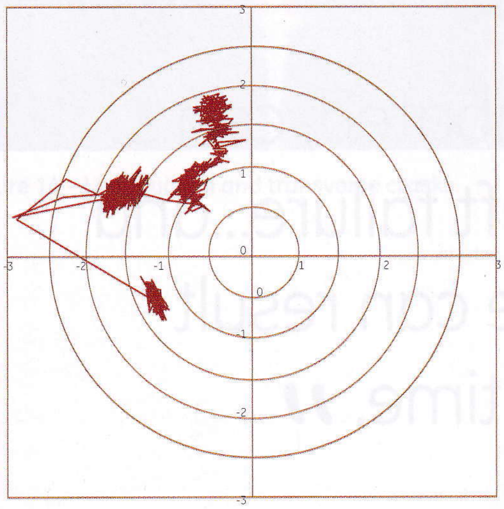


Figure 11 – Polar plot historical trend.

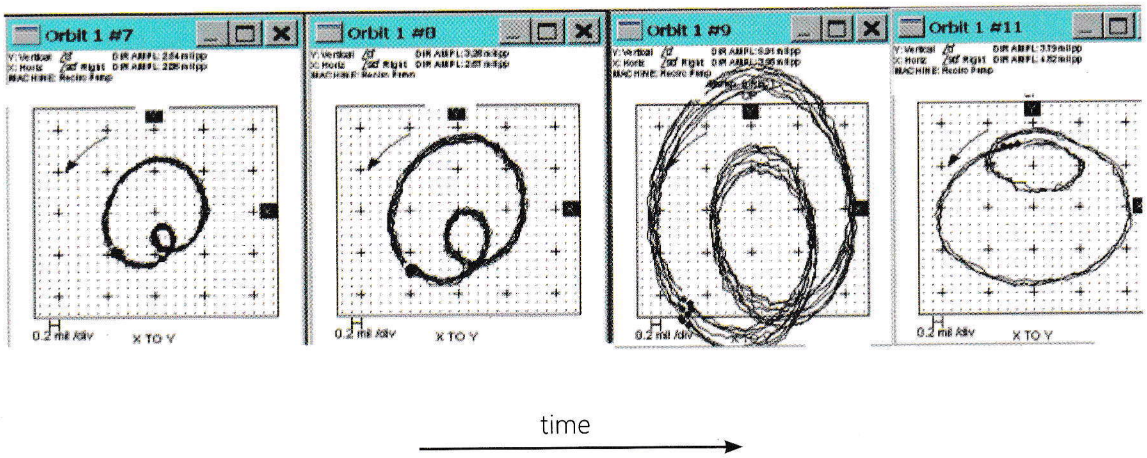


3 mils pp Full Scale

## Case History – Reactor Recirculation Pump with a Shaft Crack

The following data was acquired from an RRP operating with a cracked rotor. Figure 10 is a trend file that indicates an increase in the 1X amplitude over time. Unfortunately, phase data was not shown on this display. Figure 11 is a Polar plot that displays the erratic behavior of the 1X amplitude and phase. 2X amplitude and phase data was not measured during this time period. However, dynamic vibration data was captured and is displayed in Orbit form in Figure 12. The presence of the internal loop in the Orbit path is the result of a 2X vibration component. Over time, the 1X and 2X amplitude increased and the phase angle was also changing. Of particular interest was the 180° change of the 2X phase angle. In Figure 12, the location of the 2X vibration loop begins at the six o'clock position and ultimately shifts to the 12 o'clock position. This is a 180° phase shift over time. The amplitude of the 2X vibration also increased and decreased during the 180° phase shift. This is a classic resonance type response. A resonance frequency, initially greater than twice the operating speed of the pump, decreased in frequency due to the decrease in dynamic stiffness of the rotor. This resonance was excited by the 2X rotor vibration.

Figure 12 – Shaft Orbits.



Although the compensated vibration amplitudes were at low levels, the vibration symptoms indicated the strong possibility of a rotor crack. The decision was made to remove the pump from service and perform an inspection. Disassembly of the pump and inspection of the rotor did reveal the presence of a crack. The crack initially was propagating longitudinally along the rotor, but then turned into a transverse crack. The transverse crack was propagating around the circumference and radially inward (Figures 13 and 14).

> “Shaft cracks, if left unabated, can lead to total pump shaft failure...and significant lost revenue can result from production downtime.”

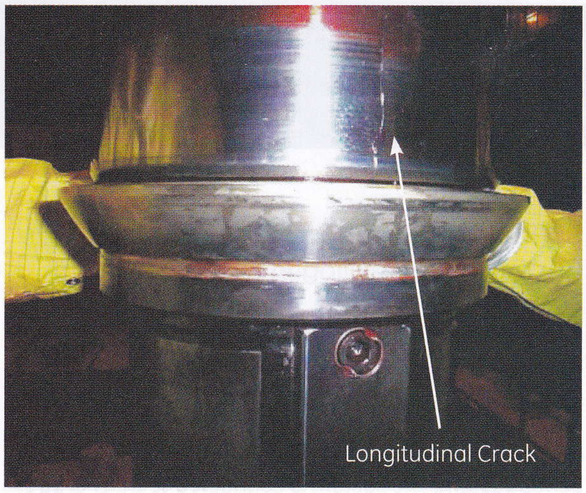


**Figure 13 – Crack initiation location.**

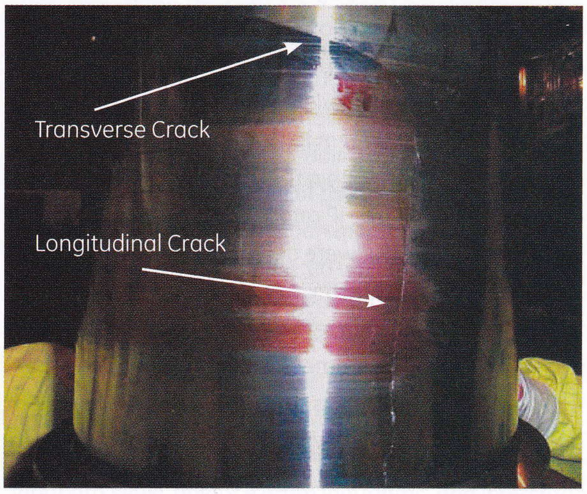
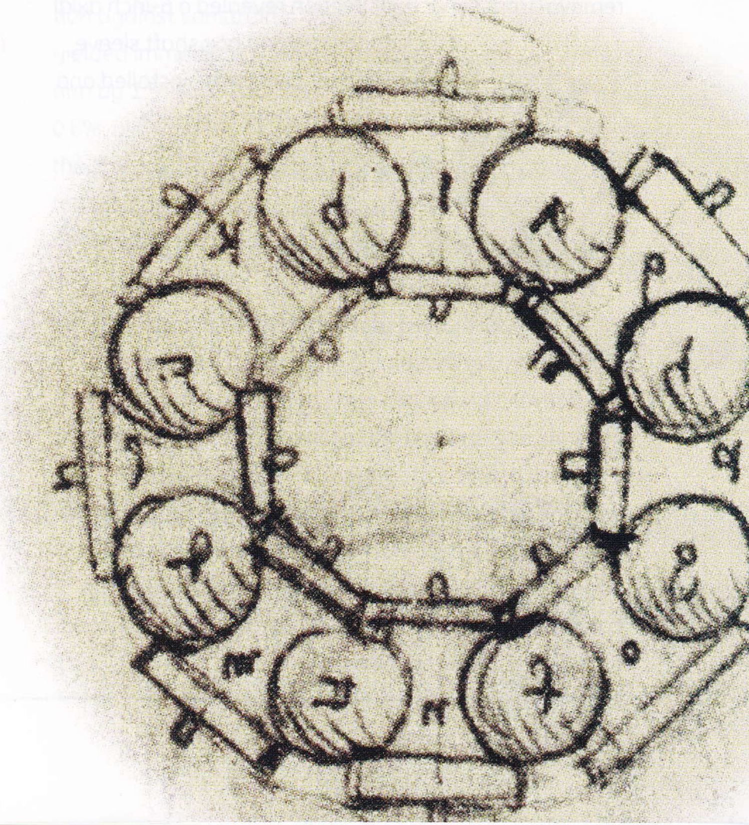


**Figure 14 – Longitudinal and transverse cracks.**

## Summary

Shaft cracks, if left unabated, can lead to total pump shaft failure. In addition to the expense of the rotor replacement, significant collateral damage to the pump assembly and internals may occur. The resulting unplanned outage time can significantly impact reliability and availability metrics, and significant lost revenue can result from production downtime. Whereas an effective monitoring system does not prevent a shaft crack event, early detection can mitigate the consequences of a total shaft failure. Computer-based systems can provide the necessary information, and, in conjunction with a diagnostic methodology focused on early detection of shaft crack behavior, catastrophic consequences can be avoided.

Editor's Note: Ronald Bosmans retired from GE Energy in October 2006. This article was originally prepared for, and presented at, the EPRI Predictive Maintenance Users Group, Vibration Forum in Annapolis, Maryland, July 2006.



# Synopsis of Savings

## Early Warning Saves a Reactor Feedwater Pump

A large nuclear plant uses two Boiling Water Reactor units, each producing more than 1 GW of electrical power. Bently Nevada™ machinery protection systems and condition monitoring software are installed on a variety of critical plant equipment, including the main turbine generators and exciters, and a variety of pumps such as Condensate, Service Water, Circulating, Reactor Recirculation, and Reactor Feed.

An alarm from the system alerted control room operators to higher-than-normal radial vibration levels on a Reactor Feed Pump inboard bearing, and examination of the trend data showed that both amplitude and phase had changed at all four radial bearing vibration transducers. The vibration response was consistent with a change in stiffness, such as from an internal rub or a cracked shaft. Based on this data, a plan was developed to remove the unit from service within hours. Upon removal from service, inspection revealed a 6-inch axial crack on the stuffing box shaft sleeve. Replacement parts were installed and the pump returned to service.

Lab examination of the fracture surfaces revealed that the crack had initiated at the sleeve's internal keyway. Further examination showed that a loose sleeve, caused by either improper machining or incorrect installation of the sleeve, allowed low-cycle mechanical fatigue of the keyway, eventually resulting in a crack. By detecting the crack before it progressed to complete sleeve failure with the pump in service, costly damage to the impeller and shaft were avoided. Further, the plant was able to conduct a controlled shutdown of the affected pump, continuing operations event-free and without the need to file an incident report.

## Condition Monitoring System Saves Customer $10 Million in First Six Months

A coal-fired power plant recently upgraded its Turbine Supervisory Instrumentation (TSI) system from casing-mounted seismic transducers to a full complement of X-Y proximity probes along with a Bently Nevada™ 3500 Series System. The system is connected to GE Energy's System 1® Software, and the customer has established a contract for remote diagnostics assistance. The unit is run under an Availability-Based Tariff, making machinery reliability and availability more critical than in the past, and providing the economic incentive to upgrade the TSI system to the newly installed hardware/software. Within the first several months of operation, a rub on the IP rotor and suspected broken blades on the LP rotor were detected by the system. The OEM advised that if the machine was stopped in the existing condition, a restart might not be possible. Consequently, the customer elected to continue operation until the appropriate spare parts could be obtained and an outage planned. When the machine was opened six months later as part of a planned (rather than forced) outage, blades were found damaged in the LP section and a rotor bow was confirmed in the IP section. By converting from a forced outage to a planned outage, and by allowing the customer to knowledgably continue to run the unit while carefully monitoring for any further degradation in condition, up to 250 days of downtime was avoided, exceeding 10 million USD in savings.

## Offshore Compressor Instability Identified During Commissioning

A large oil and gas company operates a number of offshore platforms in the North Sea. The majority of these platforms are today equipped with Bently Nevada™ continuous monitoring systems for all essential machinery, and these are connected to companion condition monitoring software, allowing the platforms to be monitored remotely from an onshore location.

During commissioning of a newly installed export compressor on one of the platforms, the unit entered Alert alarm levels and eventually tripped as a result of high vibration. The data leading up to the trip and during the coast down of the unit was captured automatically by the condition monitoring system. The commissioning team conferred with a Bently Nevada Machinery Diagnostics Services (MDS) engineer, and they quickly concluded that the data indicated a real and serious machinery problem. This problem was identified as a rub, and the machine was opened for inspection. Damage was found to the mechanical gas labyrinth seals, balance drum labyrinths, and interstage labyrinths. A complete new spare bundle with rotor was installed, but the same problem was incurred during testing of the new bundle. The problem was isolated to an instability in the balance drum area, with the unit operating very close to its margin of stability. The decision was made to replace the knife labyrinths with those of a honeycomb design instead, changing the stiffness and altering the margin of stability. The new labyrinths resolved the problem, and the unit has operated without incident since. The inclusion of online monitoring for these units has proven to be very valuable, both in identifying and resolving the problems during commissioning, and in closely monitoring the ongoing operation of the units since they operate so close to their margin of stability. Without the system, the unit would likely have been restarted following the trip, possibly resulting in severe damage. Even if the unit had continued to run without catastrophic failure, the rub would have opened seal clearances, reducing the efficiency and resulting in additional $CO_2$ and $NO_X$ emissions, both highly undesirable. This single event more than paid for the cost of the monitoring system in the first few weeks of usage.

## MVC® System Saves Millions in Ammonia Plant Application

GE Energy's patented Multi-Variable Control (MVC) system has been used for several years to provide sophisticated advanced supervisory control at a large ammonia plant, optimizing energy costs and ammonia production. The system continuously collects relevant data from the underlying distributed control system and computes/implements optimal setpoints that minimize energy consumption and maximize ammonia production against constraints. Installation of the system yielded immediate benefits, reducing energy consumption by 1.5% and boosting ammonia production by 0.6%, allowing the plant to pay back its investment in the MVC system within the first six months. In addition to these benefits, the plant has also experienced a decrease in unplanned downtime, and when downtime does occur, production is not impacted as severely as before the advanced controls were implemented.

# Pipe Strain

This case history reviews many of the problems encountered during the startup of a wet gas compressor machine train at a petrochemical facility. The machine train consisted of a 1500 kW (2000 hp) single-wheel steam turbine, speed increasing gearbox, and centrifugal compressor that was skid-mounted and assembled by the Original Equipment Manufacturer (OEM). A factory test run verified that the unit conformed to the end-user's specifications, and it was shipped to the field for installation.

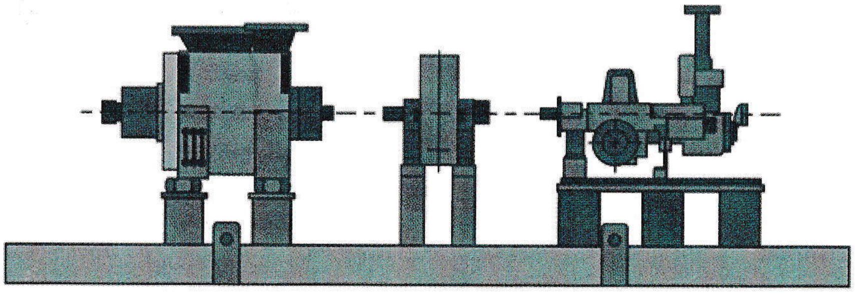
The unit was subsequently subjected to excessive piping forces causing the turbine casing to distort. Casing distortion was severe enough to break the shaft upon initial startup and to permanently deform a replacement shaft during subsequent startup attempts. Secondary damage included repeated failure of seals and bearings.

Resolution of the problems required numerous piping design changes, extensive foundation repairs, and replacement of the turbine-to-gearbox coupling. Additionally, the turbine was returned to the manufacturer for testing to ensure the casing had not suffered permanent distortion. Seal and bearing design changes were also made during the turbine testing.

The extensive problems proved very costly—several million U.S. dollars—in terms of labor and material as well as lost production due to a six-month delay in plant startup.

Dave W. Fahy, P.E.
Senior Field Engineer
Optimization & Control Services
GE Energy
dave.fahy@ge.com

**Figure 1 – Skid-mounted Wet Gas Compressor Train showing (left to right) compressor, speed-increasing gearbox, and single-wheel steam turbine.**



## Pipe Strain Basics

Skid-mounted machine trains are becoming more common as packaged units are considered to be quick and easy to install (Figure 1). Machine trains can be test run in the factory, shipped to the customer, and installed as a single unit.

Care must be taken during shipping and installation of the assembled unit, particularly to the mounting and adhesion mechanism between the skid and the concrete foundation. External forces applied to the machine train at the suction and discharge nozzles (pipe strain) must be kept within the OEM's force and moment specifications, preferably no more than half the allowable limits. Even though the accompanying piping system is carefully designed to be within these limits, problems can occur in at least two ways. One is that the calculations themselves can be in error. The other is installation-related. Those responsible for installing the piping, hangers, and associated apparatus can introduce strain not accounted for in the design if specifications and calibration requirements are not carefully adhered to.

This case history does not attempt to determine the specific causes of the excessive pipe strain. Instead, it focuses on the effects such pipe strain introduces in rotating machinery, and how pipe strain was deduced as a fundamental root cause of problems on the wet gas compressor under consideration.

## Initial On-Site Findings (First Startup)

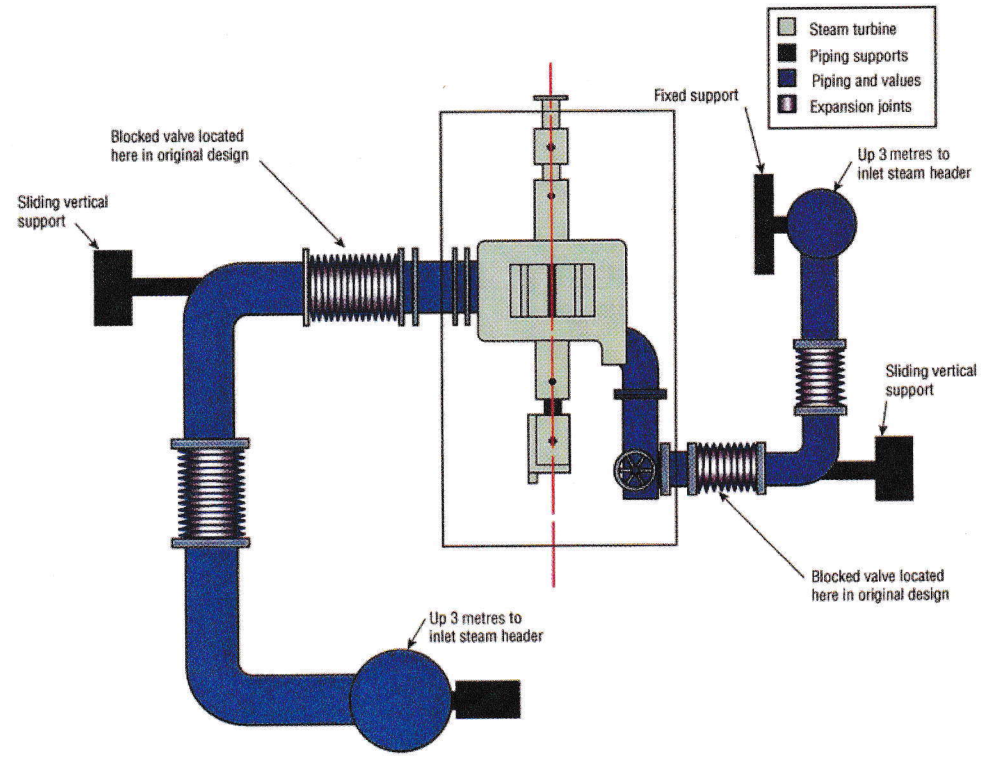
The original steam piping was designed to ensure that less than 80% of the allowable forces and moments would be present on the turbine inlet and exhaust flanges. Nevertheless, it was believed that pipe strain caused the turbine shaft to fail during its initial solo run. This occurred when the turbine casing distorted to such an extent that the carbon steam seal rings made full contact with the shaft. The resulting rub generated sufficient heat to bow, and then crack, the turbine shaft within several hours.

Major revisions to the piping system design were then implemented. Double expansion joints were added to the inlet and exhaust sides of the steam turbine (Figure 2). The revisions were such that less than 50% of the allowable forces and moments would be present on the turbine inlet and exhaust flanges. Although the revised piping installation did conform to the design specifications, there were concerns about the materials of construction, stability of the supports, and calibration of the pipe hangers. There were also safety concerns regarding the use of bellows expansion joints on the inlet steam line which operated at 50 kg/cm$^2$ @ 400°C (700 psig @ 750°F). Exhaust steam conditions were 11 kg/cm$^2$ @ 170°C (150 psig @ 360°F).

The end-user was advised to completely remove the piping system and install a system with much larger thermal loops. However, the recommendation was rejected and operation continued with the existing modifications.

Other concerns that surfaced during the initial on-site inspection of the machine involved the handling of the skid and the foundation integrity. It was learned that a spreader bar used to lift one end of the skid bent during the original installation and the unit dropped to the ground. The exact height from which the unit was dropped was never verified but was believed to be 30–60 cm (12–24 in). The quality of the anchor bolt material, the anchor bolt installation, and the grouting technique used to secure the skid were also questionable.

**Figure 2 – Initial modifications to piping arrangement surrounding the steam turbine. View is looking down from above the steam turbine.**


Steam turbine
Piping supports
Piping and values
Expansion joints
Fixed support
Blocked valve located here in original design
Sliding vertical support
Up 3 metres to inlet steam header
Sliding vertical support
Blocked valve located here in original design
Up 3 metres to inlet steam header

## Second Startup (First Piping Modification)

Using the permanently installed Bently Nevada™ 3300 machinery protection system and a portable ADRE® data acquisition system, vibration data was recorded from slow roll to approximately 5000 rpm. Initial low speed data suggested a light rub might have occurred. Because these vibration amplitudes were small, the plant elected to continue with the startup and machine speed was increased. Vibration levels remained low into the 4000-rpm range, but at approximately 4380 rpm, the vibration started to increase. Intermittent rubs occurred, indicated by the flat areas on the timebase waveform (Figure 3). Vibration levels were as high as 18 μm pp (0.72 mil pp) at the coupling end. At 4880 rpm and with operating clearances diminished due to the turbine casing distortion, a hard rub occurred in the seal area at the coupling end of the turbine (Figure 4). The startup was aborted as a result, and turbine speed was reduced to 500 rpm.

Optical measurement points were then installed on the turbine, baseplate, soleplate, and support I-beams. Initial measurements were taken with the steam piping

Figure 3 – Orbit/timebase plot at 4380 rpm showing evidence of light rub at turbine inboard bearing during second startup.

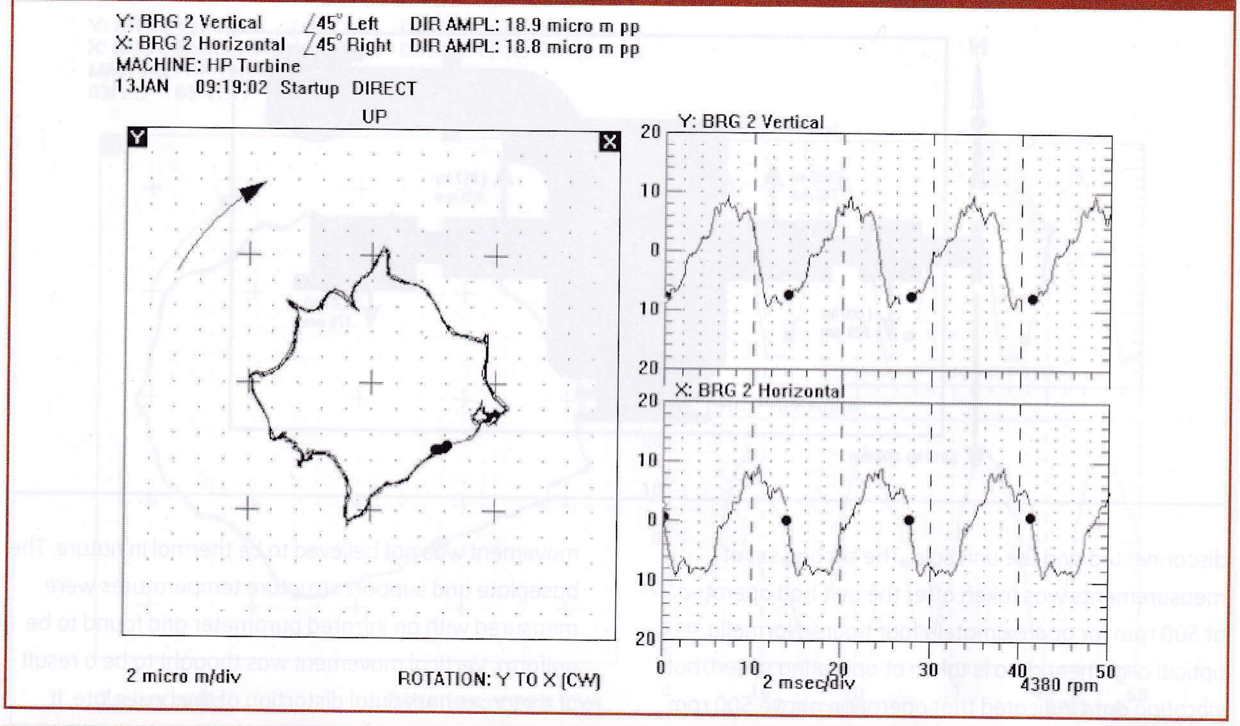


Figure 4 – Orbit/timebase plot at 4880 rpm showing evidence of hard rub at turbine inboard bearing during second startup.

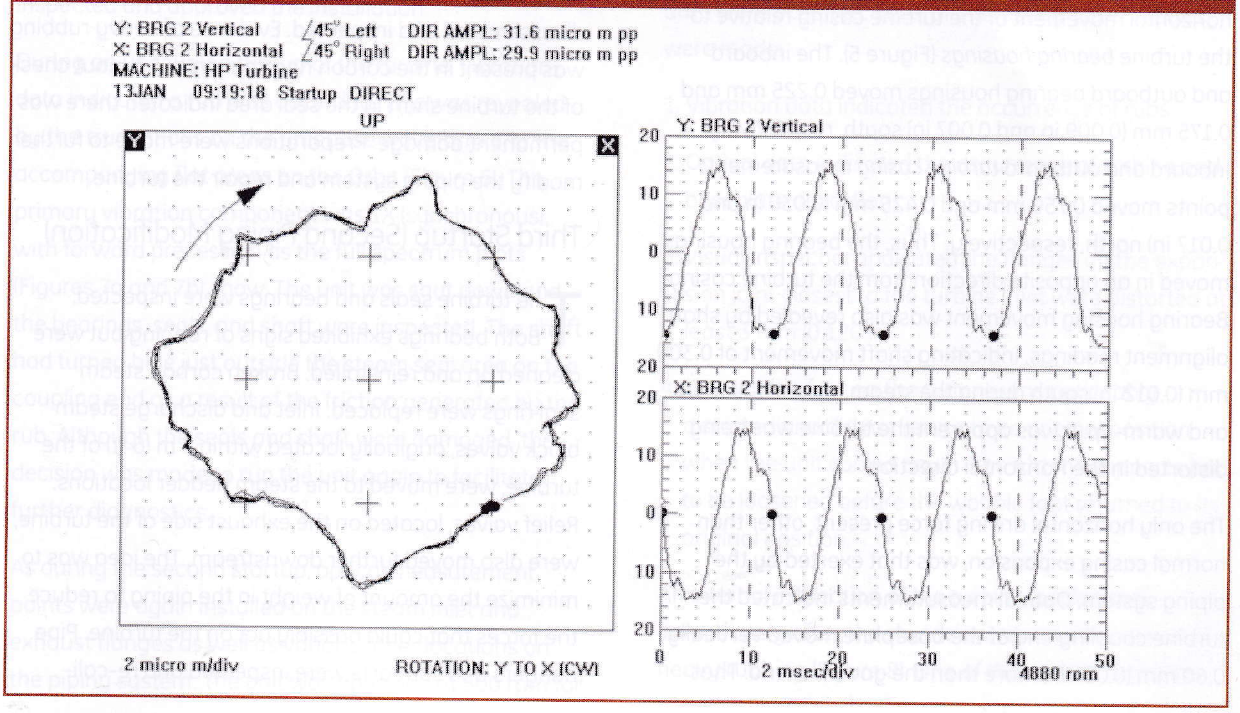
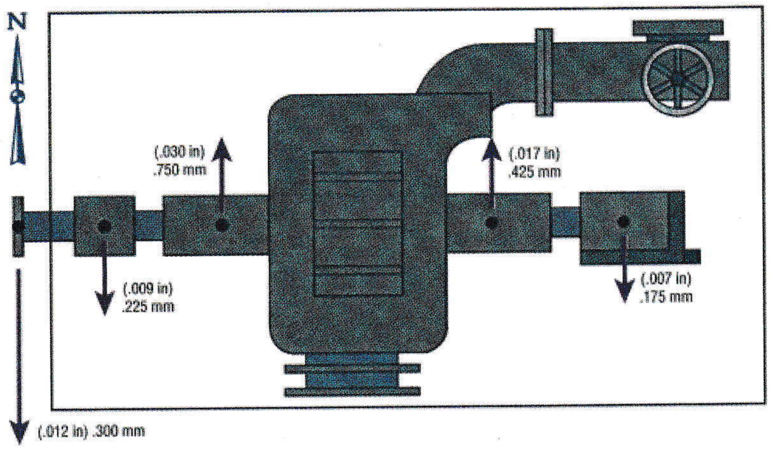


Figure 5 – Horizontal movement of steam turbine casing relative to bearing housings during steam piping warm-up.



disconnected and the unit cold. The second set of measurements was taken after the unit had operated at 500 rpm for approximately four hours. Normally, optical alignment data is taken at operating speed, but vibration data indicated that operation above 500 rpm would be unsafe.

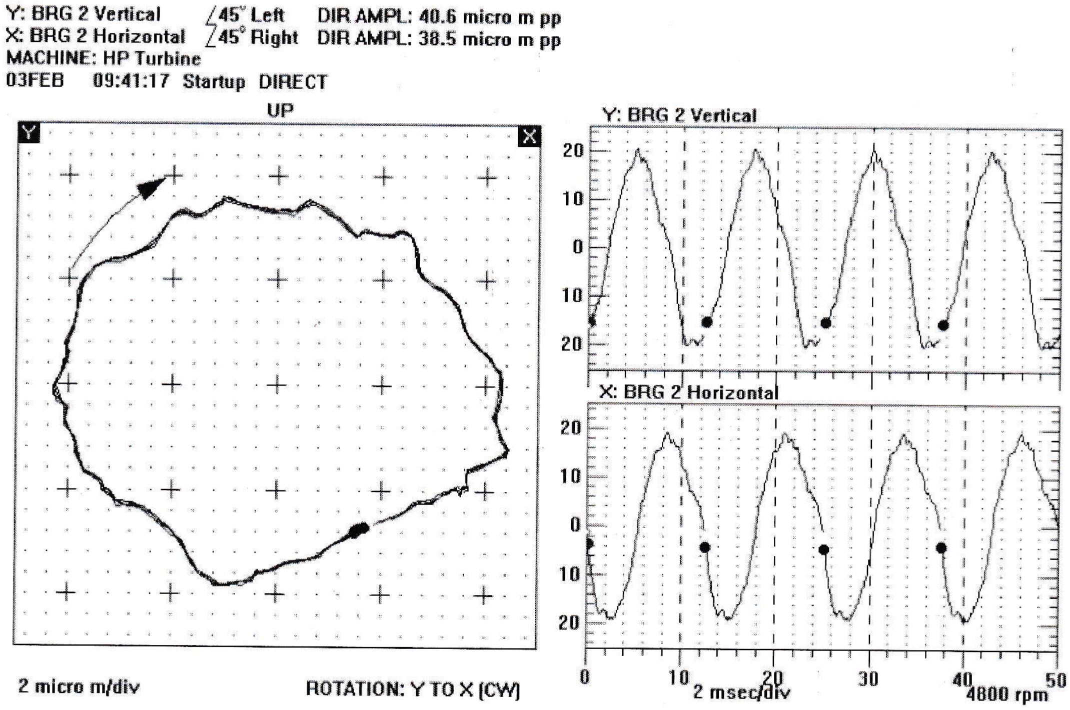
Significant information was obtained regarding the horizontal movement of the turbine casing relative to the turbine *bearing housings* (Figure 5). The inboard and outboard bearing housings moved 0.225 mm and 0.175 mm (0.009 in and 0.007 in) south, respectively. Inboard and outboard *turbine casing* measurement points moved 0.750 mm and 0.425 mm (0.030 in and 0.017 in) north, respectively. Thus, the bearing housings moved in an opposite direction from the turbine casing. Bearing housing movement was also revealed by shaft alignment readings, indicating shaft movement of 0.300 mm (0.012 in) south during the steam pipe installation and warm-up. It was apparent the turbine was being distorted in the horizontal direction.

The only horizontal driving force present, other than normal casing expansion, was that exerted by the piping system. Optical measurements indicated the turbine coupling end of the baseplate moved vertically 0.60 mm (0.024 in) more than the governor end. That movement was not believed to be thermal in nature. The baseplate and support structure temperatures were measured with an infrared pyrometer and found to be uniform. Vertical movement was thought to be a result of the gross horizontal distortion of the baseplate. It was recommended that the piping system design and installation be reviewed and modified as necessary to minimize the forces on the turbine. The turbine was disassembled and inspected. Evidence of heavy rubbing was present in the carbon ring seal area. A runout check of the turbine shaft in the seal area indicated there was permanent damage. Preparations were made to further modify the piping system and repair the turbine.

## Third Startup (Second Piping Modification)

The turbine seals and bearings were inspected. Both bearings exhibited signs of rubbing but were cleaned up and reinstalled. Broken carbon steam seal rings were replaced. Inlet and discharge steam block valves, originally located within 2 m (6 ft) of the turbine, were moved to the steam header locations. Relief valves, located on the exhaust side of the turbine, were also moved further downstream. The idea was to minimize the amount of weight in the piping to reduce the forces that could possibly act on the turbine. Pipe hangers and supports were inspected and re-cali-

Figure 6 – Orbit/timebase plot at 4800 rpm showing evidence of rub at turbine inboard bearing during third startup.



brated. Field engineers from the pipe design company inspected and approved the installation.

During an uncoupled run-up of the turbine, vibration data indicated a rub was occurring. This was revealed by the truncations on the timebase waveform and the accompanying flat areas on the Orbit (Figure 6). The primary vibration component was 1X (synchronous), with forward precession as the full spectrum plots (Figures 7a and 7b) show. The unit was shut down and the bearings, seals, and shaft were inspected. The shaft had turned blue just outside the steam seal area on the coupling end as a result of the friction generated by the rub. Although the seals and shaft were damaged, the decision was made to run the unit again to facilitate further diagnostics.

As during the second startup, optical measurement points were again installed on the steam inlet and exhaust flanges as well as various other locations on the piping system. The unit was operated at 500 rpm for approximately three hours while vibration and optical data were acquired. Several interesting observations were made:

1. Vibration data indicated the occurrence of rubs.
2. Optical data indicated the occurrence of turbine and baseplate distortion.
3. Visual inspection indicated the flanges on the expansion joint closest to the turbine inlet were distorted at least 3 mm (0.120 in).
4. The wobble foot on the turbine was noticeably distorted and did not return to its original position when the unit cooled down. The turbine supports had to be loosened before the wobble foot returned to its original position.

An internal inspection of the turbine, performed immediately after the shutdown, revealed evidence of heavy rubbing (Figure 8). One of the carbon seals had

Figure 7 – Full spectrum showing predominance of forward precession for 1X component during third startup at a) turbine outboard bearing and b) turbine inboard bearing.

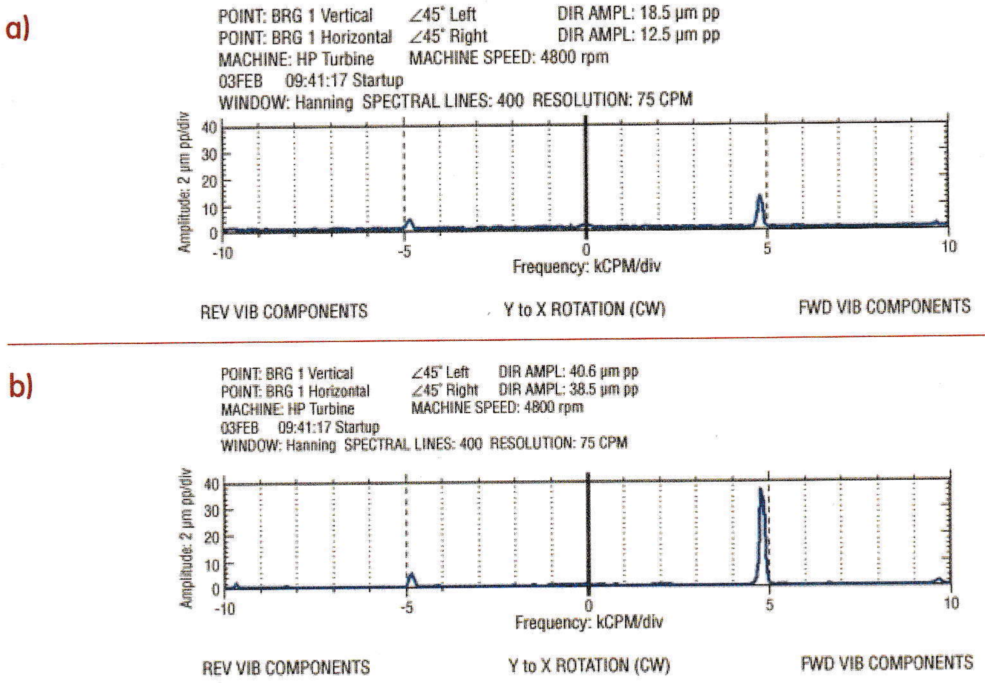
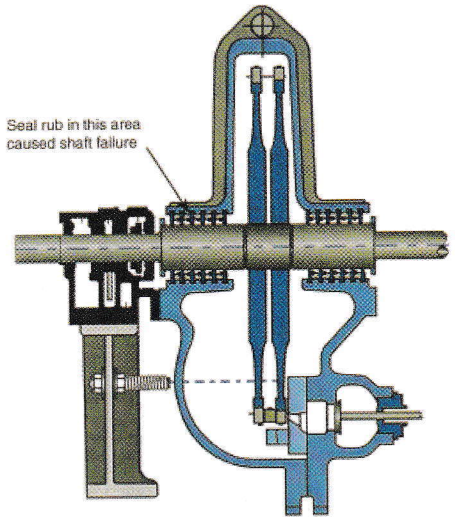


Figure 8 – Turbine cross-section showing rub location.

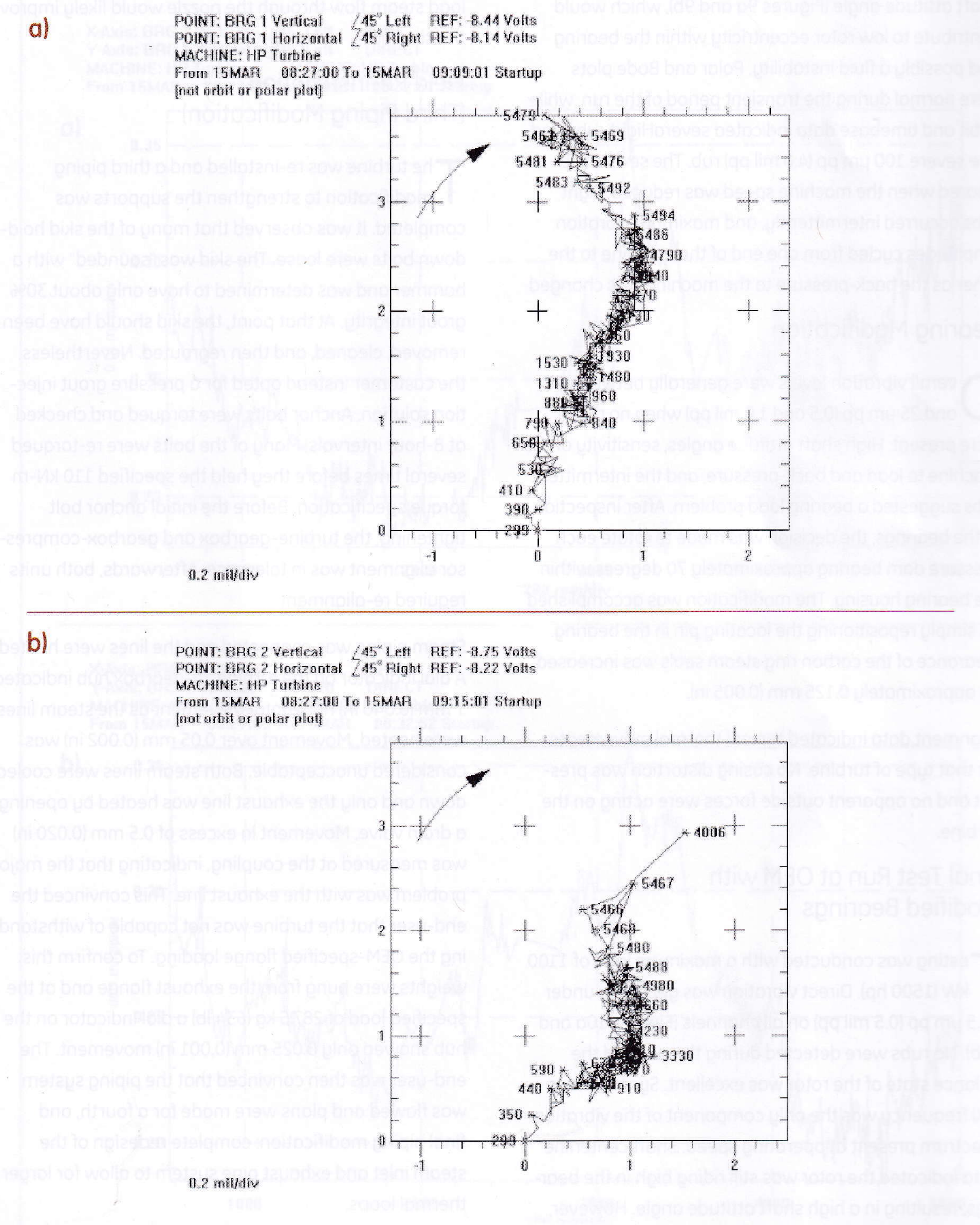


spun and was broken in several pieces and the shaft was permanently damaged. The rotor was removed and the internal alignment of the turbine case was checked. Significant runout in the nozzle ring [0.75 mm (0.030 in)] and seal area [0.325 mm (0.013 in)] warranted the return of the turbine to the manufacturer for closer inspection.

## Shop Test at OEM Factory

Concerned that damage may have occurred when the skid was dropped during the original installation, the turbine was completely disassembled and inspected. No damage was found. The nozzle ring and seal areas were adjusted back into tolerance. The turbine was placed on the test stand with a new rotor, bearings, and seals, and a cold optical survey was conducted. The unit was coupled to a water brake, an 1121 kW (1500 hp) load was applied, and vibration data was collected. After one hour at load, hot optical measurements were made.

Figure 9 – Shaft centerline plot showing vertical rise of the shaft within a) turbine outboard and b) turbine inboard bearings.



Vibration data indicated that the rotor rose straight up in each bearing [100 µm (4 mils) governor end and 37.5 µm (1.5 mils) coupling end]. This resulted in a high shaft attitude angle (Figures 9a and 9b), which would contribute to low rotor eccentricity within the bearing and possibly a fluid instability. Polar and Bode plots were normal during the transient period of the run, while Orbit and timebase data indicated several light rubs and one severe 100 µm pp (4.0 mil pp) rub. The severe rub cleared when the machine speed was reduced. Light rubs occurred intermittently, and maximum vibration amplitudes cycled from one end of the machine to the other as the back-pressure to the machine was changed.

## Bearing Modification

Overall vibration levels were generally between 12 and 25 µm pp (0.5 and 1.0 mil pp) when no rubs were present. High shaft attitude angles, sensitivity of the machine to load and back-pressure, and the intermittent rubs suggested a bearing load problem. After inspection of the bearings, the decision was made to rotate each pressure dam bearing approximately 70 degrees within the bearing housing. The modification was accomplished by simply repositioning the locating pin in the bearing. Clearance of the carbon ring steam seals was increased by approximately 0.125 mm (0.005 in).

Alignment data indicated typical thermal movements for that type of turbine. No casing distortion was present and no apparent outside forces were acting on the turbine.

## Final Test Run at OEM with Modified Bearings

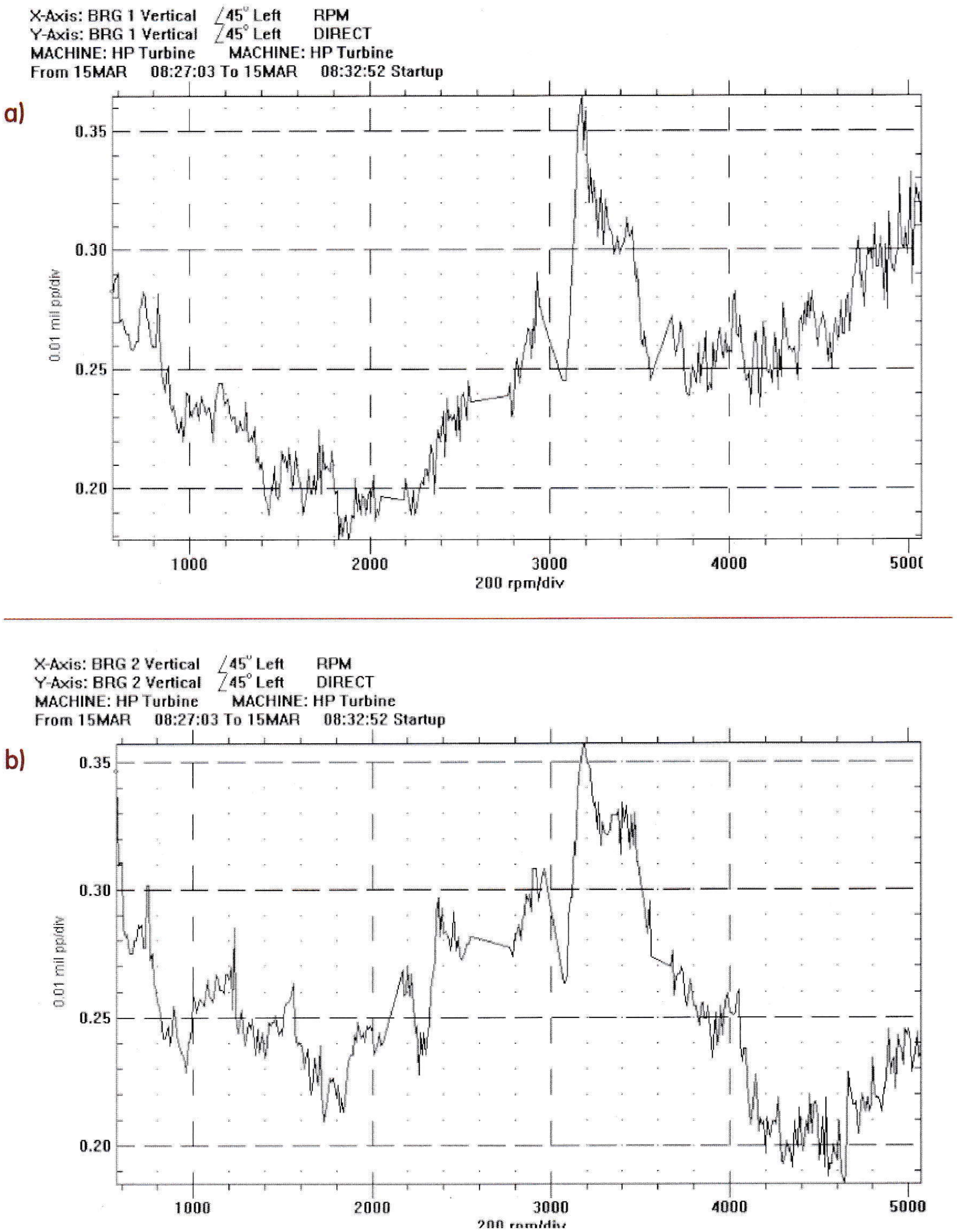
Testing was conducted with a maximum load of 1100 kW (1500 hp). Direct vibration was generally under 12.5 µm pp (0.5 mil pp) on all channels (Figures 10a and 10b). No rubs were detected during the run and the balance state of the rotor was excellent. Synchronous (1X) frequency was the only component of the vibration spectrum present at operating speed. Shaft centerline data indicated the rotor was still riding high in the bearings, resulting in a high shaft attitude angle. However, the machine was much less sensitive to load and back-pressure changes due to the bearing modification. The OEM believed that the high shaft attitude angle was due to partial arc steam forces lifting the rotor and that full load steam flow through the nozzle would likely improve the situation.

## Field Re-installation (Third Piping Modification)

The turbine was re-installed and a third piping modification to strengthen the supports was completed. It was observed that many of the skid hold-down bolts were loose. The skid was "sounded" with a hammer and was determined to have only about 30% grout integrity. At that point, the skid should have been removed, cleaned, and then regrouted. Nevertheless, the customer instead opted for a pressure grout injection solution. Anchor bolts were torqued and checked at 8-hour intervals. Many of the bolts were re-torqued several times before they held the specified 110 kN-m torque specification. Before the initial anchor bolt tightening, the turbine-gearbox and gearbox-compressor alignment was in tolerance. Afterwards, both units required re-alignment.

Steam piping was connected and the lines were heated. A dial indicator on the turbine-to-gearbox hub indicated 1 mm (0.040 in) horizontal movement as the steam lines were heated. Movement over 0.05 mm (0.002 in) was considered unacceptable. Both steam lines were cooled down and only the exhaust line was heated by opening a drain valve. Movement in excess of 0.5 mm (0.020 in) was measured at the coupling, indicating that the major problem was with the exhaust line. This convinced the end-user that the turbine was not capable of withstanding the OEM-specified flange loading. To confirm this, weights were hung from the exhaust flange and at the specified load of 287.6 kg (634 lb) a dial indicator on the hub showed only 0.025 mm (0.001 in) movement. The end-user was then convinced that the piping system was flawed and plans were made for a fourth, and final piping modification: complete redesign of the steam inlet and exhaust pipe system to allow for larger thermal loops.

Figure 10 – Overall vibration amplitude versus shaft rotative speed during shop testing at a) turbine outboard and b) turbine inboard bearings.



## Success (Fourth Piping Modification)

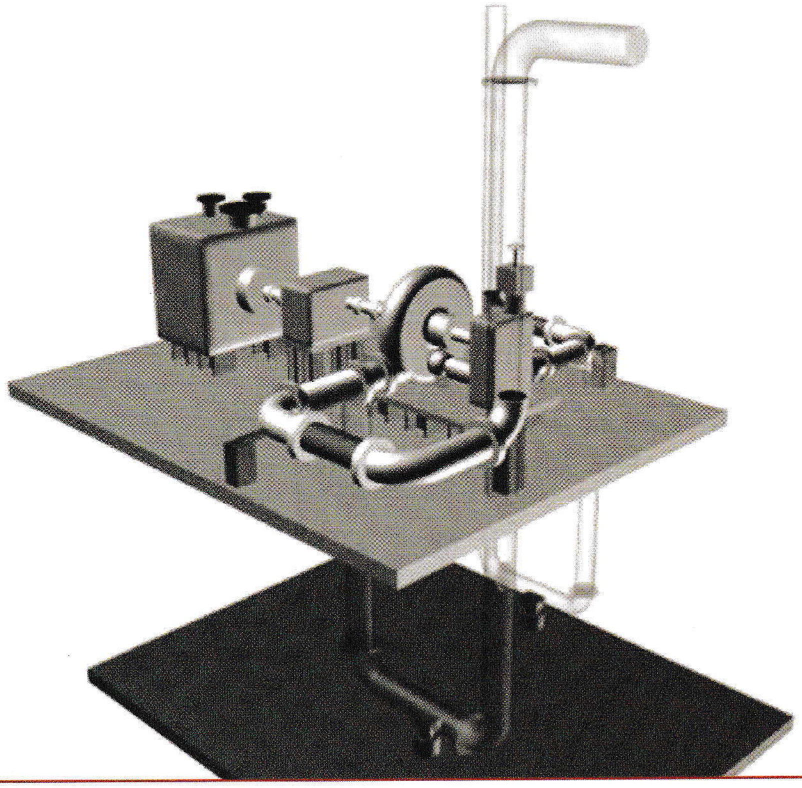
Figure 11 depicts the final pipe design as an overlay of the expansion joint modification. Notice particularly that the thermal loops were expanded down to grade level. Foundation repairs improved the stability of the skid, and, approximately six months after the first startup attempt, the unit finally went into production.

## Conclusion

As this case history demonstrates, pipe strain can be a significant source of problems that manifest themselves in machinery behavior. In this case, the root problems stemmed from a piping system, and subsequent revisions did not actually meet engineering specifications despite analysis with computer programs and third-party review. A final design employing larger thermal loops minimized the forces exerted on the turbine, allowing it to finally be brought into service.

While the initial problems were unfortunate, they were compounded unnecessarily by attempts to "patch" a poor piping design rather than redesign it entirely. Lost production alone totaled several million dollars, not to mention labor and material costs. Had the original recommendations to completely re-do the piping design been followed, the unit could have been online within one month.

Figure 11 – Final piping arrangement.



## Rayong Electrical Generating Company (REGCO) of Thailand Recognized for Excellence in Technology Optimization

GE Energy congratulates REGCO for winning the "Excellence in Technology Optimization Award" at the Asian Power Awards 2006 held in Singapore last September. Routinely exceeding availability targets, REGCO attributes their success to their proactive asset management and willingness to involve advanced technology.

In 2000, REGCO selected GE Energy's System 1® optimization and diagnostic software as the foundation of a systematic program to continuously monitor the critical and essential machinery at their Rayong Power Plant. Then in 2005, the system was supplemented with GE Energy's EfficiencyMap™ thermodynamic performance monitoring software. By improving the plant's operational thermal efficiency, REGCO achieved project payback less than a year after commissioning EfficiencyMap.

The Asian Power Awards are organized by the Charlton Media Group, the publishers of Asian Power magazine, and recognize those in Asia's power industry whose efforts stand out.

ASIAN
POWER
AWARDS
2006

## 2007
## Training

Customers around the world rely on our extensive technical training to help them gain the skills they need to get the maximum benefit from our hardware, software, and service offerings. We offer instruction ranging from online or CD-based self-paced material through multiple-week sessions that cover entire diagnostic programs.

In 2007, we will be offering over 200 courses at our numerous global training centers, helping ensure that you can find a convenient date and location no matter where you are located. Or, if you prefer, these courses can also be presented at your site.

For details on any of our condition monitoring, reliability program development, machinery diagnostics, systems and instrumentation, thermodynamic performance, and other courses, visit us online at www.ge-energy.com/oc/techtraining